NASA/CP—2000–210332

The Spacelab Accomplishments Forum

Edited by
J. Emond
NASA Headquarters, Washington, D.C.

Compiled by
N. Bennett
Universities Space Research Association
Huntsville, Alabama

D. McCauley
University of Alabama in Huntsville
Huntsville, Alabama

K. Murphy
Mevatec Corporation
Huntsville, Alabama



Proceedings of a forum
held in Washington, D.C.
March 10–11, 1999

June 2000

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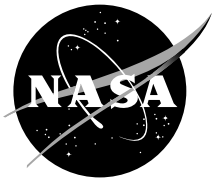
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Sponsored in part by
the National Research Council
and the Boeing Company

Cover image taken during the
STS–9 Spacelab–1 mission

National Aeronautics and
Space Administration

Marshall Space Flight Center • MSFC, Alabama 35812

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MAR 17 2000

Dear Spacelab Forum Participants:

Last year, I had the pleasure of meeting many of you at the Spacelab Accomplishments Forum, held at the National Research Council on March 9 and 10, 1999. It is now my pleasure to present a report highlighting presentations from that forum.

The engineering challenges met, international collaboration fostered, and research achievements obtained over Spacelab's 17-year legacy will not be forgotten. The International Space Station will carry the advances forward into the next century.

I hope you will enjoy the report.

Sincerely,

Daniel S. Goldin
Administrator

Enclosure

Spacelab Accomplishments Forum
Report Format

This report highlights the series of Spacelab Accomplishments presentations made on March 10 and 11, 1999 at the National Research Council, Washington, D.C. Given the wide range and levels of experience background among our audience participants at the forum, panel presentations did not seek to provide in-depth research analyses comparable to specific discipline technical conferences that are held. The forum, and this report, are, however, good synopses of the spacecraft's development and range of research accomplished through the Spacelab series of missions. The report is in the order of the presentations as they were made during the forum.

Spacelab Accomplishments Forum Agenda

March 10, 1999

Welcome and OLMSA Overview of SPACELAB Program
Arnauld Nicogossian, MD, OLMSA Associate Administrator 9:00-9:15

From Sojourn to Settlement: Spacelab to ISS
Mr. Joseph Rothenberg, Associate Administrator Office of Space Flight 9:15-9:30

Spacelab's Role in Fostering a Global Space Community
Mr. John Schumacher, Associate Administrator Office of External Relations 9:30-9:45

Overview of SPACELAB, European Space Agency Perspective
Mr. Allan Thirkettle, former Spacelab Project Manager 9:45-10:15

Building and Operating Spacelab - Spacelab Design and Systems Engineering Panel 10:30-12:00
- Mr. Axel Roth, panel moderator, Marshall Space Flight Center
- Mr. Klaus Berge, representative, German Space Agency (DLR)
- Dr. Robert Benson, former Director, NASA HQ Flight Systems Division and Spacelab Mission Integration
- Mr. Allan Thirkettle, former Spacelab project manager
- Mr. Harry Craft, former Manager, Payload Projects Office

Earth Observations
- Dr. Jack Kaye, program scientist associated with the ATLAS program 1:15-2:00

Space Sciences
- Dr. Arthur Davidsen, Johns Hopkins University 2:00-2:45

Spacelab Life Sciences Research 3:00-5:10
- Dr. Frank Sulzman, panel moderator, OLMSA, NASA Headquarters
- Dr. Muriel Ross, NASA/Ames Research Center
- Dr. Lawrence Young, MIT
- Dr. Ken Baldwin, University of California at Irvine
- David Robertson, MD, Vanderbilt University

Mercury, Skylab, Spacelab, Spacehab, International Space Station: A Continuum 5:10-5:30
- Dr. Charles Walker, former Space Shuttle Payload Astronaut, Manager, Space Programs Marketing, Boeing/Washington D.C. Operations

March 11, 1999

International Participation in Spacelab Panel	8:30-10:00
Dr. Roger Crouch, panel moderator, OLMSA, NASA Headquarters	
Dr. Horst Binnenbruck, German Space Agency/DLR	
Dr. Shunji Nagaoka, National Space Development Agency of Japan/NASDA	
Mr. W. Riesselmann, Head, ESA Microgravity Payloads Division	
Spacelab Commercial Research Panel	10:15-11:45
Mr. Joel Kearns, panel moderator, NASA/Marshall Space Flight Center	
Dr. Louis Stodieck, BioServe Space Technologies	
Dr. David Klaus, BioServe Space Technologies	
Dr. Weija Zhou, Wisconsin Center for Space Automation and Robotics	
Dr. Al Sacco, Center for Advanced Microgravity Materials Processing	
Microgravity Science Research Panel	1:00-3:15
Dr. Bradley Carpenter, panel moderator, OLMSA, NASA Headquarters	
Dr. Eugene Trinh, Jet Propulsion Laboratory	
Dr. Lawrence DeLucas, University of Alabama at Birmingham	
Dr. David Larson, State University of New York at Stony Brook	
Dr. Martin Glicksman, Rensselaer Polytechnic Institute	
Dr. Simon Ostrach, Case Western University	
Closing Remarks	4:00

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Report Introduction
Dr. Arnauld Nicogossian

For those of you who attended our forum, despite a late winter storm, I thank you for your perseverance; your presence there contributed to the success of our event. When Office of Life and Microgravity Sciences and Applications first considered hosting a two day Spacelab Accomplishments Forum, we were faced with a daunting challenge. How could we effectively recognize the achievements of Spacelab, a program that was multi-discipline, multi-national, multi-faceted with new ground broken in engineering/ spacecraft design and development, mission management and flight integration, payload development and operations; with a range of over 800 material science, space science, life science, Earth observation and commercial research investigations during 17 years of flight from 1981 to 1998? The simple answer is: we could not, even if the two-day event extended into two weeks. We chose instead to provide an overview, a snapshot of the challenges faced and successes gained by the Spacelab program. If, after two days, the audience in this forum walked away with the belief that Spacelab was a key milestone in the development of international space collaboration; was a spacecraft workhorse that fostered a broad range of research activities spanning widely separate fields of endeavor; and paved the way for international space research on board the International Space Station, then we will have fulfilled our goals for the forum.

The history of Spacelab is impressive. Designed and developed by the European Space Agency, with the Remote Manipulator Systems (RMS) developed by Canada, Spacelab's emergence as a reusable research module paralleled the Space Shuttle's emergence as NASA's first reusable crewed spacecraft. The second flight of the Shuttle in 1981 saw the use of the Spacelab pallet for NASA's then Office of Space and Terrestrial Applications to conduct Earth science research. The last Spacelab mission, Neurolab, was flown in 1998. Neurolab was probably one of the most complex space biomedical research missions put together. It involved several international agencies, and was part of the "Decade of the Brain," promulgated by the United States Congress to understand the function of the nervous system in health and disease.

As a program, Spacelab lasted 17 years; the 36 missions flown included both pallet type and pressurized volume. A total of 375 days of flight time was logged and there were 16 pressurized module missions. Spacelab was not only a precursor to the International Space Station, but played a role in collaborative research with Russia's space station Mir. Spacelab docked to Mir at a time when Mir did not have a laboratory that we could use. Before we deployed US/Russian laboratories on Mir, Spacelab carried a set of instruments to Mir to conduct experiments and return the astronauts and cosmonauts.

Spacelab has proven its versatility in many ways. By our very preliminary estimates, 800 distinct investigations were carried out, 1,000 refereed articles were published, 3,000 talks and abstracts were delivered, and over 250 Master of Science and Ph.D. degrees were granted as a result of the Spacelab research. There were major contributions to advancing knowledge in the areas of life sciences, microgravity sciences, genetics, human physiology, combustion (we have rewritten textbooks on soot formation), gravitational biology, and protein crystallography. Spacelab also fostered commercial research efforts to develop new or improved products on Earth using knowledge gained from the unique environment of space. Apart from the research my office supports, significant research was undertaken in space science and Earth observations.

One of the most fascinating stories about Spacelab is the discovery of the ancient caravan routes, which led us to the finding of lost water wells along roads which were covered by sand long ago. When these wells were opened up, they were able to improve irrigation in some areas.

Spacelab also made a significant contribution to education and outreach by providing insights into human spaceflight. People were living and working in space and conducting educational sessions from space in the areas of physics, chemistry, biology and engineering, space and Earth sciences. The program inspired our youth through the involvement of national math and science teacher's associations which have been working to develop a curriculum for students in the U.S. and abroad.

Spacelab missions included major international participation. The European Space Agency and the countries of Germany, United Kingdom, Japan, India, France, Switzerland, Australia, Canada, Belgium, Italy, Russia, and the United States were among the regular contributors to research.

Spacelab is a tribute to thousands of individuals. Scientists, teachers, astronauts, and payload specialists dedicated themselves to ensure that research was completed. Our international partners worked across many time zones to link science mission controls together. Let us not forget the dedication of the mission managers and flight crews who worked so intensely to ensure that we got all the data; who worked so hard to make sure that equipment repairs were made in real time in order to obtain data downlinked, and to ensure mission success. It was therefore fitting to use the auditorium of the National Research Council to bring together a few of the many contributors to summarize and pay tribute to the accomplishments and relive the excitement of discovery.

As International Space Station elements are deployed, bringing to reality the vision of an on-orbit multinational laboratory to spearhead research advances in space in the 21st century, we can look with pride at the legacy of Spacelab and the dedication of thousands of individuals around the world so ably represented by the panel members and forum audience.

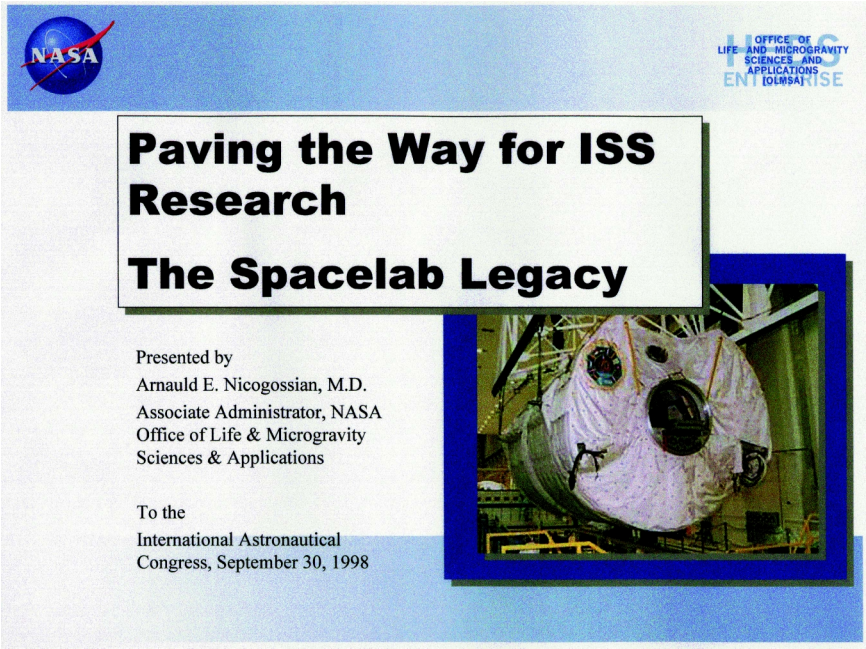


Figure 1: Introduction.

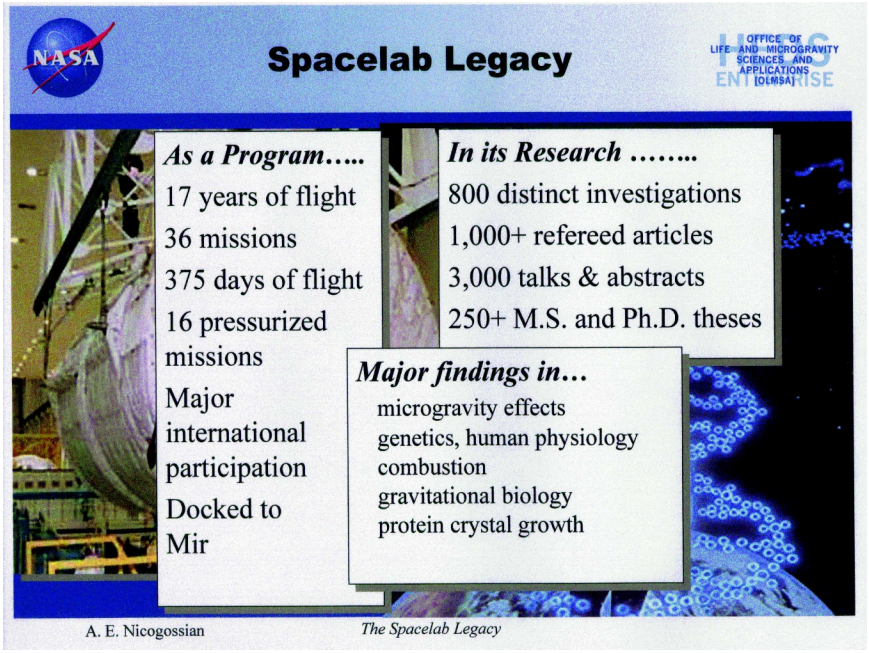


Figure 2: Spacelab Legacy.



Figure 3: International Perspective.

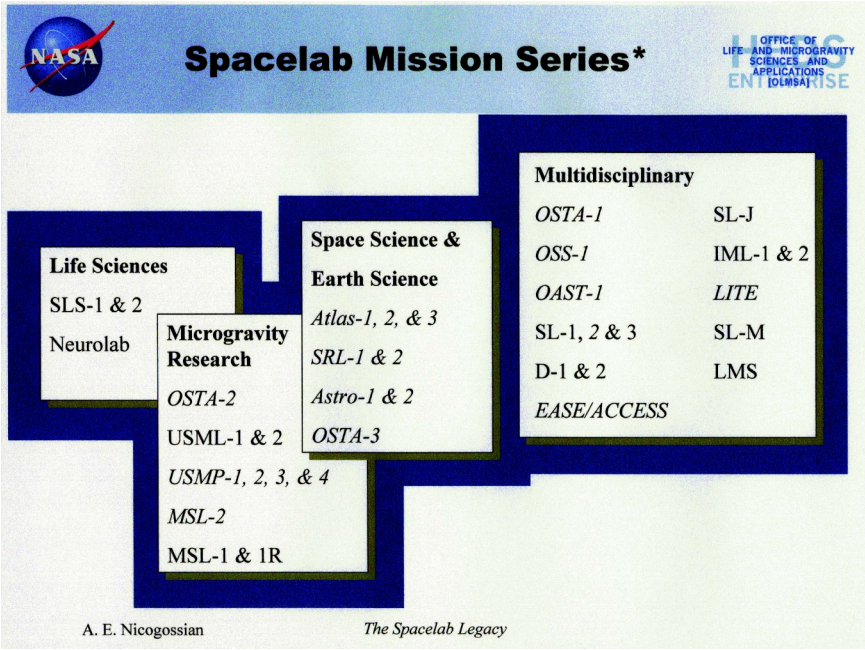


Figure 4: Spacelab Mission Series.

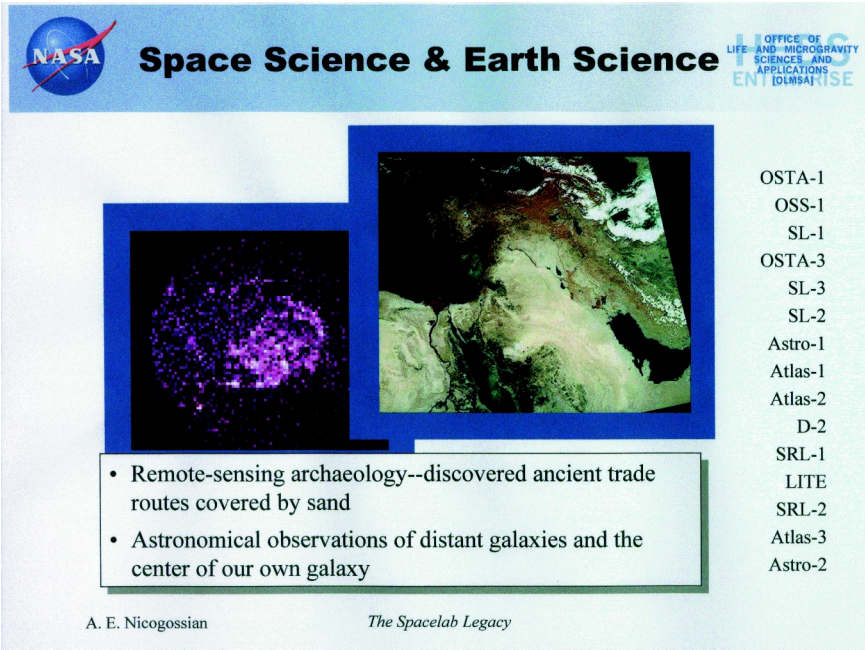


Figure 5: Space Science and Earth Science.

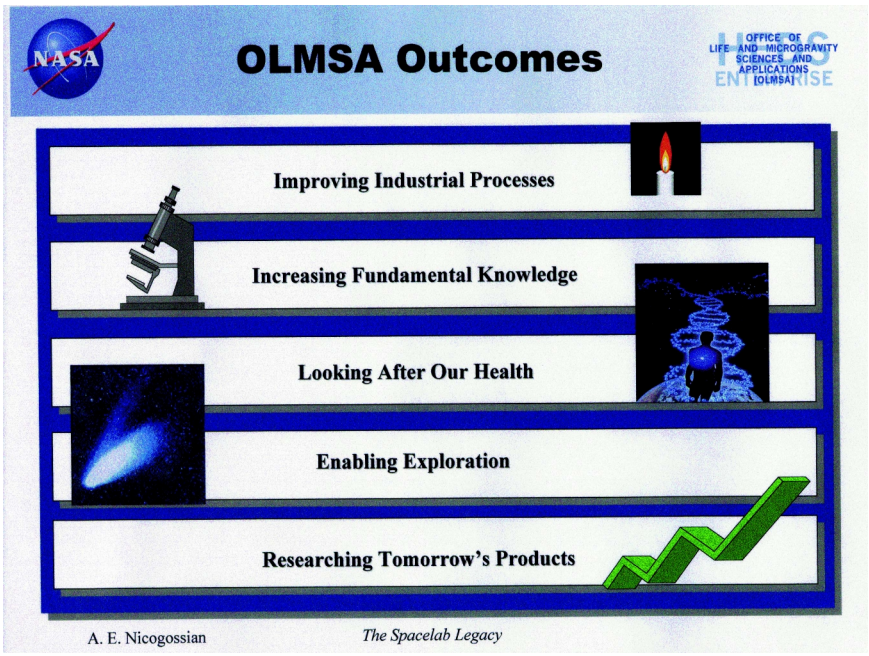


Figure 6: OLMSA Outcomes.

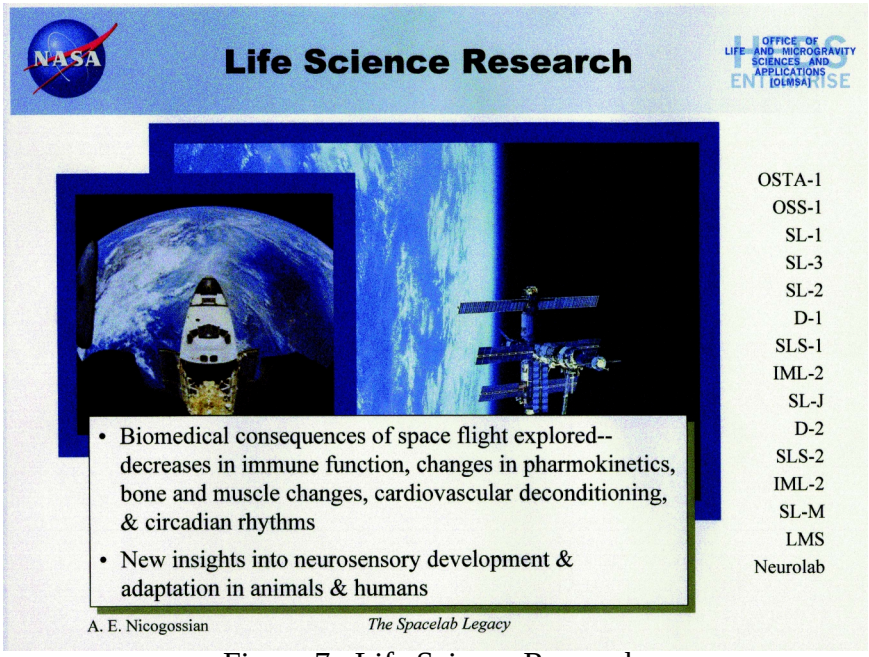


Figure 7: Life Science Research.

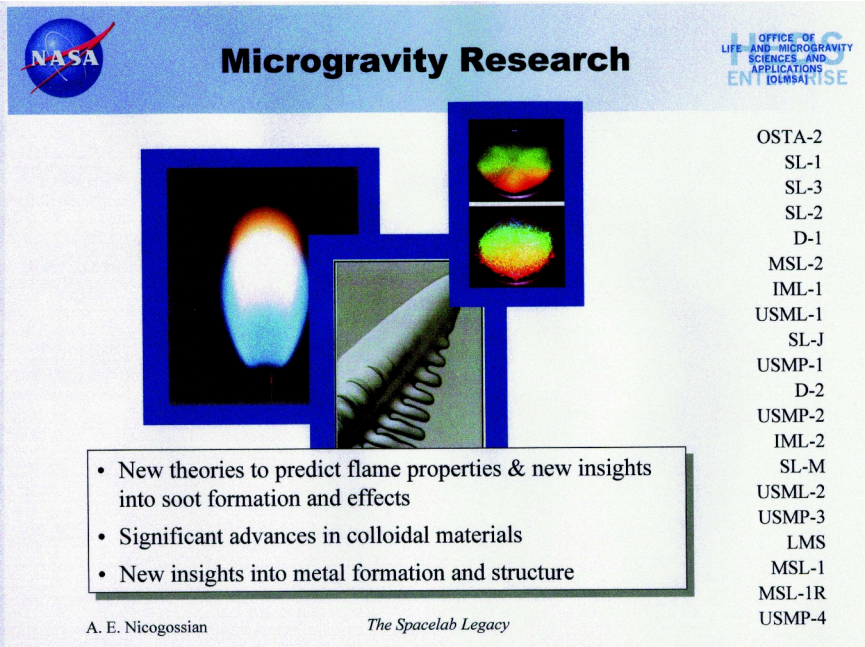


Figure 8: Microgravity Research.

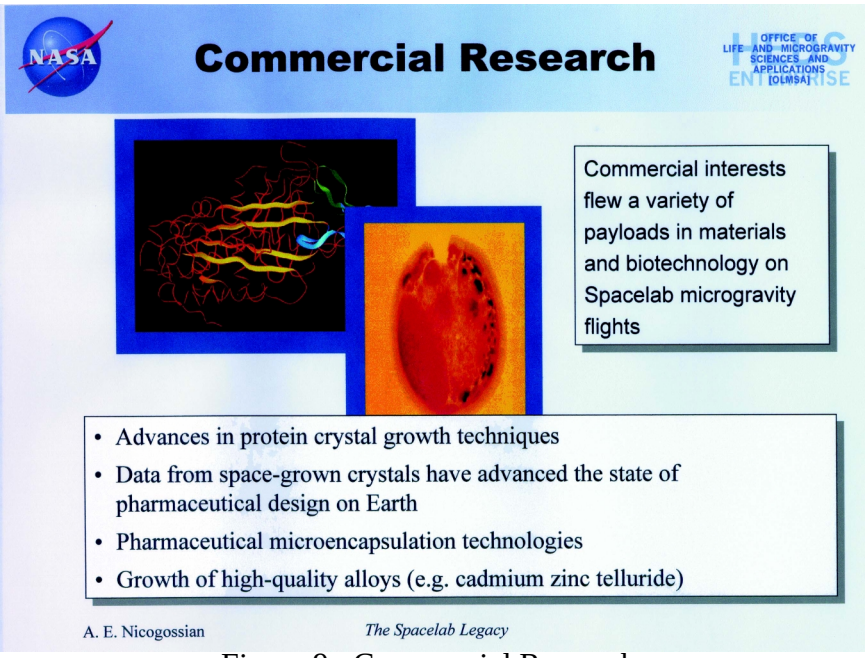


Figure 9: Commercial Research.

From Sojourn to Settlement: Spacelab to ISS
Mr. Joseph Rothenberg

I think the measure of the Space Station will not be that we have a larger football field piece of hardware up there; it will be the results of the research program and the fact that it is a research facility. Hopefully, it will provide and enable the research that we currently envision, but more importantly, enable the research that we cannot envision today.

We had a saying back in Hubble, before the initial launch in 1990, when I was in the operations world, "conscious expectation of the unexpected." Unfortunately, the unexpected at launch was really unexpected and we had to go fix it. Nevertheless, I think the research program today and the science that it is returning is rewriting textbooks and reshaping a lot of theoretical views of the universe, and I think there is plenty more to come.

I only hope, as we put Space Station in place, that it provides the facilities and really does allow us to look and do research in an environment in a different way than we currently envision such that we extract a lot more out of it than we expect today and/or can envision today. And, in the future, we will have these forums and be talking about accomplishments that we wouldn't have envisioned. I don't want to speculate about how successful it will be, but I want to make sure that we put a facility up there that enables it and then let you determine how successful it will be.

Let me reflect now on Spacelab. I actually got involved in Spacelab, it seems to me to be in the mid-1970s. It even may have been earlier than that. When I worked for Grumman, a number of people that I worked with were called upon to help with the environmental control system for Spacelab. I was part of this little group.

It was looked upon at that time with a promise, and I think the fact that you are here talking about accomplishments bears that out. It was the first and is the first multipurpose research laboratory to be put in space.

Its pallet provided external unpressurized capabilities, and then provided pressurized capabilities for human interaction for research. It covered all the sciences: Earth, space science, microgravity, materials science and, with that, life sciences, and it really did set the stage for the future. We took the next step in putting some research on board Mir and learning how to do long duration research.

From my background in robotic spacecraft, I think that we have a lot to learn about how to utilize a space station. Instead of having long preparation periods and perfectly executed time lines for a two-week opportunity in space, which is sort of how you operate with the Shuttle (on Mir, it was a little different), on Station we are going to be up there for a long time.

One of the things we need to learn is how to make the most efficient use of all onboard resources. This will allow us to have problems and recover quickly and turn around quickly — much more autonomously than having an entire team on the ground reworking time lines and things like that.

We are going to put a set of tools up there. One of the things we did with Hubble was to put an observatory up there. We designed the ground operations and everything else to maximize the efficient utilization of that observatory.

If you looked at a model of all the places in the universe you might want to look at with Hubble and did a statistical average for 30 days — putting together what the viewing might be and taking into account the occultation from the Earth — the amount of interesting targets that might not get occulted that were in some of what appeared at the time to be less populated and uninteresting parts of the sky, you looked at an average efficiency of 37 percent.

So, we designed the ground system. We tweaked the planning and scheduling system and did everything under the sun to get up to that 37 percent. We spent probably $500 million on the ground system, or more, just to get a ground system in place that would optimize the use of the observatory.

When we got it up there, we really learned how to use it. They were achieving efficiencies of 60 and 70 percent. Part of that, at times and on average, was well into the 40 to 50 percent range. You can actually get 100 percent efficiency by looking at the star at the pole and just going around. Rather uninteresting if you just wanted to chase statistics. These were high priority scientific targets.

My message here is that we learned how to use Spacelab when it got up there. We thought we knew how to use it. We spent a lot of time in planning and a lot of money, but we really learned how to use it when it got up there. I think with Space Station, we've got a lot to learn.

I think one of the things we can do as a facility provider, and that's what I look at myself as, building a research park up there, is to try to make access to it as simple and as efficient as possible from the ground. To put in place, and ensure that we have in place, remote access and telescience, so you don't have to go to a NASA center. Instead, you can interact with it from your university and, ultimately, through the Internet from your home. Wherever you have a PC and can plug into the Internet, you can interact with it and carry out your science. That will be important if we learn how to use this thing routinely. If there is a problem and they need to contact you the easiest way to let you look at some data and look at some results and you will say, "Hey, here is what I need."

We need to put in an infrastructure. I talk about it as an infrastructure, but I really mean something that takes advantage of commercial access to the Internet, not another specialized NASA network, that allows flexibility and interaction with it.

I think we need to reduce the time and the overhead it takes to get an experiment on board. We need to minimize the uniqueness of each investigator's safety and development plan such that we can concentrate on spending the individual's resources on the science program and the investigation, not on the overhead to get on board the Station.

We've got a lot to learn about improving our safety processes. Today, you all have firsthand experience and I have alleged experience or information that says you may deal with a NASA center which happens not to be the primary center or even in the primary center that is operating it. If you are dealing with a NASA center first, you've got to go through their safety ritual and ensure you are ready. Then, you may have to go through another one in an intermediate center if you are operating out of Marshall, and finally, the Shuttle safety process and maybe processing at the Cape, depending on what kind of science.

In many cases, these processes use different documentation, require different inputs, and have different reviews. That probably can't be the case in all cases, because I think the community would have revolted by now. Nevertheless, there is still a lot of that in place. I know it from firsthand experience when I was running Goddard by hearing our own investigators and hearing people who had to deal with us. We need to take that and fix it.

One of the things that the Space Telescope Science Institute did for Hubble was to make the mechanics of executing an observation transparent to the user. The user proposed the science, what he wanted to look at, what wavelengths, and what instruments he thought he wanted to look at.

After that, the process took over and carried it out. He could interact with it at any point that he needed to, but he didn't have to understand how they made the sausage. He just had to know at the other end he was going to get some data, and he needed to have some check points along the way to give him confidence.

It wasn't autonomous in that we just said, "Okay, we will point it and take your observation and send you the data, and if you are happy, you win; if you're not, you try again; get to the end of the line." The scientist was interactive enough that we knew when we were going to execute his observation it was going to execute what he wanted to do, but he didn't have to understand all the mechanics, and he could access. We need to provide that same kind of service to the community that will be using Station off in the future, and we have some activities underway to do that.

The routine telescience I mentioned already is another important thing: increasing the efficiency of utilization. We've got facilities; we've got power; we've got crew time; we've got data links and communications links. We've got to find a way to make sure that we take maximum advantage of all of those resources such that we are not allowing one resource, or lack of one resource, to drive the whole schedule. How can we plug in things that don't need active crew time but take advantage of bandwidth when there is something going on that is interactive and doesn't need the bandwidth? Again, as we get up there, we are going to have to learn how to refine and increase the efficiency of utilization.

A lot of the science we are doing in space, and a lot of the activities that are non-science we are doing up there, is an investment in the future. We need to get young people in this country excited about science and engineering. Whether they go into space science, or whether they go into science and engineering and go off and do world-class research at NIH on the ground or at some university or teaching hospital or go into the applications of science. I think that is what we are all about.

With a lot of the things we are doing, the benefits are not going to pay off today, but they are going to pay off years from now. We need to motivate and excite the next generation of scientists and researchers to

carry forward our research programs, what we are setting out to do, because many of these are many years away from completion.

The educational component of what we are doing needs to be, I think, supported by NASA and by all the community better than it is today. This means reaching out beyond the university level, getting to the high school students, getting to the younger students in more ways than we are today. That could be an insatiable kind of requirement put on us, which we need to control. On the other hand, I think that we need to do far more than we are doing today. Hopefully, I will help enable that.

I also hope that once a year we are going to be in here talking about not only our accomplishments, but also what we can do better to make the Station a better research facility for the community. I'd like to make that interactive. We are going to learn together. I think you are going to have to have some patience and we are going to have to have some patience for listening and trying to improve each year on what we are learning as we are carrying out the research program.

I look forward, in a few years from now, to having these on an annual basis and maybe even more frequently than that if necessary. I look forward to interacting and learning what we can do to improve the Station and improve service and facilities to the research community. I look forward to, hopefully, being here to hear them in person.

Spacelab's Role in Fostering a Global Space Community
Mr. John Schumacher

It's a moving experience to be here for this important forum. I am very humbled as I look back and try to really recreate the work that many of you here have done. I can tell you, it was fascinating listening to Arnauld Nicogossian and Joe Rothenberg giving you their experiences with Spacelab. Just to put things in perspective, I think it's not hard to figure out that, when you all were working on the Spacelab Memorandum of Understanding (MOU), I was in my sophomore year at the Naval Academy trying to get an oceanography degree. You all have done tremendous things! During my remarks I hope to highlight some of your key accomplishments. (Figure 1.)

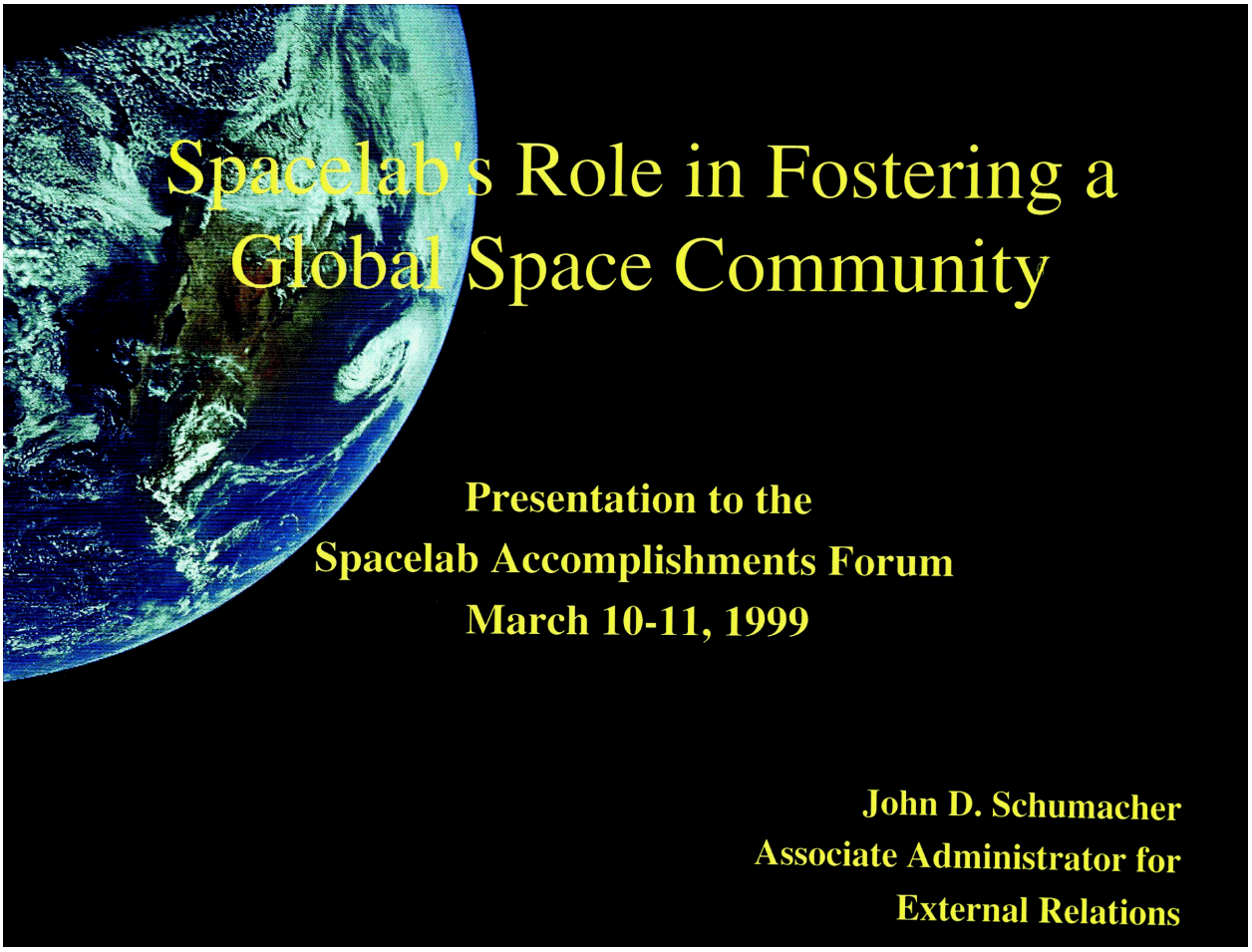


Figure 1. Introduction.

The Spacelab Accomplishments Forum is significant not only for highlighting the scientific accomplishments realized with the use of this unique laboratory, but also it marks a critical milestone. For, in recognizing the history and achievements that have been realized through the Spacelab series of missions, we

also recognize that this was a critical step in the evolution of space exploration internationally. With its final mission, which Arnauld and Joe have highlighted, Neurolab STS-90, we are ready to begin the year where we will have a permanent human presence in low orbit using the International Space Station.

The Spacelab program was critical to researchers, to engineers, to scientists, and to policymakers. Because of its size and scope, it would provide us with a tool and as we learned how to use it properly, it would teach us how to work effectively together to realize amazing things.

What I would like to touch on today are three aspects of it. I think you will hear plenty about both the scientific accomplishments as well as engineering accomplishments. I just want to touch quickly on three key points: historical perspective; the Spacelab, how it actually came together with Europe and the United States; and its legacy for the future. (Figure 2.)



Figure 2. Agenda.

First, the historical perspective. It's difficult, standing so close to the edge of the next century and where we are today, to fully appreciate how unique the Spacelab program was in the evolution of space flight internationally. I know that sounds trite because we have said it over and over for about ten years now, but I can tell you — from one touching it reasonably fresh and at arm's length — it's truly impressive. (Figure 3.)

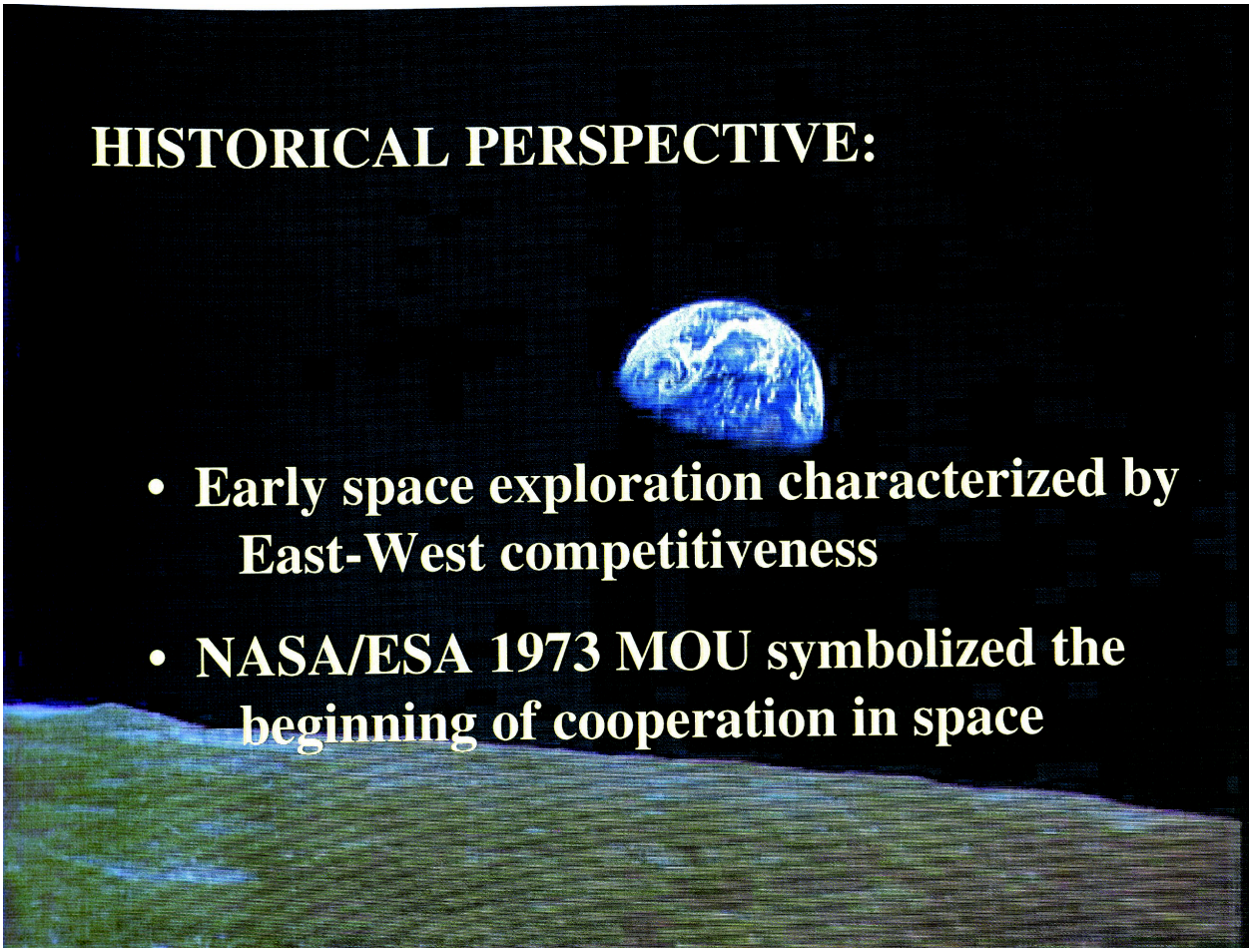


Figure 3. The Historical Perspective.

Today, we have two elements of the International Space Station up and we are looking forward to the Service Module going up this year and looking towards permanent human presence on ISS. We are seriously considering the technologies to provide the follow-on to the Space Shuttle and those that will take us once again beyond the Earth's gravitational field. We are more than two decades away from when NASA and the European Space Agency first agreed that ESA would design and build the Spacelab, a truly bold step.

When NASA and ESA signed the 1973 Memorandum of Understanding creating the Spacelab, the Space Shuttle program had only received Presidential approval in January of the previous year.

Apollo 17, the final Apollo mission, had flown in December of 1972. Détente was in the air after two decades of superpower rivalry.

The date of the first Apollo/Soyuz test project had been set during the Nixon-Kosygin summit in 1972 and was still three years away from launch. This was a time when the East-West space competitiveness that had characterized the early days of spaceflight had begun to ease.

And very importantly, the spaceflight nations were beginning to look for new cooperative opportunities. Nations in Europe and the United States seized that opportunity and moved forward on Spacelab.

Listed here are the countries involved with and in Europe and actually moving forward with the MOU on the Spacelab program. (Figure 4)



Figure 4. International Participation.

It was in the emerging environment that I discussed, the early mid-1970s, that NASA and ESA agreed on a program that would bring 11 nations together to develop a pressurized laboratory at the same time the Shuttle was moving forward in its development. Suddenly, a pressurized laboratory 180 miles above the surface of the Earth would be accessible to the international research community. Life and microgravity sciences research could be conducted on a greater scale both in quantity and in frequency than during previous years.

In its 17 years of service, the Spacelab would surpass our wildest expectations. It would fly 36 times. It would carry a variety of international hardware, and its missions would involve investigators from Europe and all around the world. I think that is what is key, that a bold step was made to put together a pressurized laboratory involving international cooperation. Then, those initial nations moved beyond that and tried innovative techniques to bring in researchers from all around the world.

The Spacelab, as we know, also conducted missions exclusively for Japan and Germany. It would also be a part, as Dr. Nicogossian talked about, of the first Shuttle/Mir rendezvous mission in June 1995. So, over and over again, Spacelab was used in new and innovative ways.

Besides being an incredible platform on which to perform research, a topic you will hear about throughout the day, the program also expanded opportunities in the international community. While the Apollo astronauts had all been American, now there were opportunities for astronauts from other nations to fly. The first Spacelab mission, STS-9, in November 1983, carried ESA astronaut Ulf Merbold from Germany as a member of the six-person crew.

The program was also teaching our American, European, and other scientists and researchers from all around the world to work together in the highly demanding and complex world of human spaceflight and pressurized volume research in human spaceflight.

On to the future. Both Joe [Rothenberg] and Arnauld [Nicogossian] talked about Space Station and how Spacelab was the legacy (Figure 5). Many tend to look at Space Station as a logical step. I think it's a giant step, and if we are true to the Spacelab heritage, we will make it a giant step. The people that worked on Spacelab, that put it together, that put the push that went through on Spacelab... if we carry forward that construct and that context of thought and we push to be just as innovative as those folks were in going from where we were into the Shuttle Spacelab era, in moving forward into the Shuttle Station era and beyond, we will be very well served.

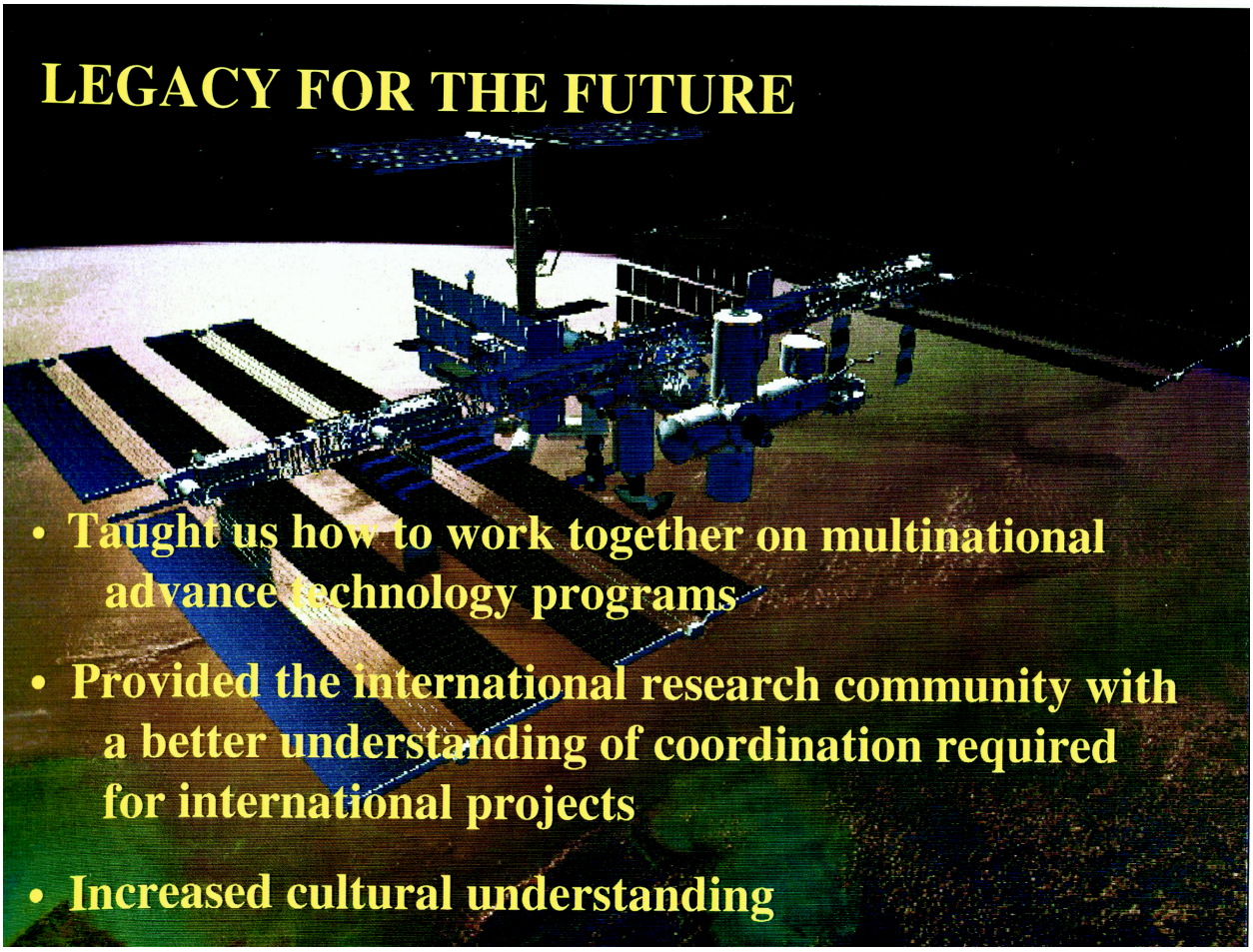


Figure 5. Legacy of Spacelab.

Many questions remain, as Arnauld [Nicogossian] and Joe [Rothenberg] also talked about, on how to best use, how to manage, how to conduct research on Station. For those who have lived through the Spacelab era, many of the research and integration processes flow naturally. What we need to do is understand that, and then challenge. I think the two prior speakers are spending a lot of time doing that, challenging: "Here are some neat ways we are trying to go. Are there different and new ways we should come at and do that and really try to make a push on that?"

That will be the true legacy of Spacelab into the new millennium. When we take the lessons we learned, and I don't just mean rotely transfer them to Station, but take those innovative and bold models and push them into new arenas and new ways on the Space Station.

For NASA, the bottom line remains that if we continue to be as innovative, dedicated, and cooperative as an international partnership as we have been through our use of Spacelab, then we will fulfill this legacy. We will use the Station to the limit of the way it was designed to be used in the years ahead.

Joe and Arnauld also talked about increasing the frequency of this kind of discussion. I would point to the first International Space Station partnership meeting on the uses of Space Station which will be hosted by the European Space Agency in Berlin in June of 2000. That will be the next exciting leap-off point as we continue this type of discussion.

Thank you very much again for letting me share a few minutes of thought with you today.

Overview of SPACELAB, European Space Agency Perspective
Mr. Allan Thirkettle

I have the somewhat awesome responsibility of giving a European perspective, which is fine. Unfortunately, I have 30 minutes in which to do it and I think 30 days may not be enough. (Figure 1.)

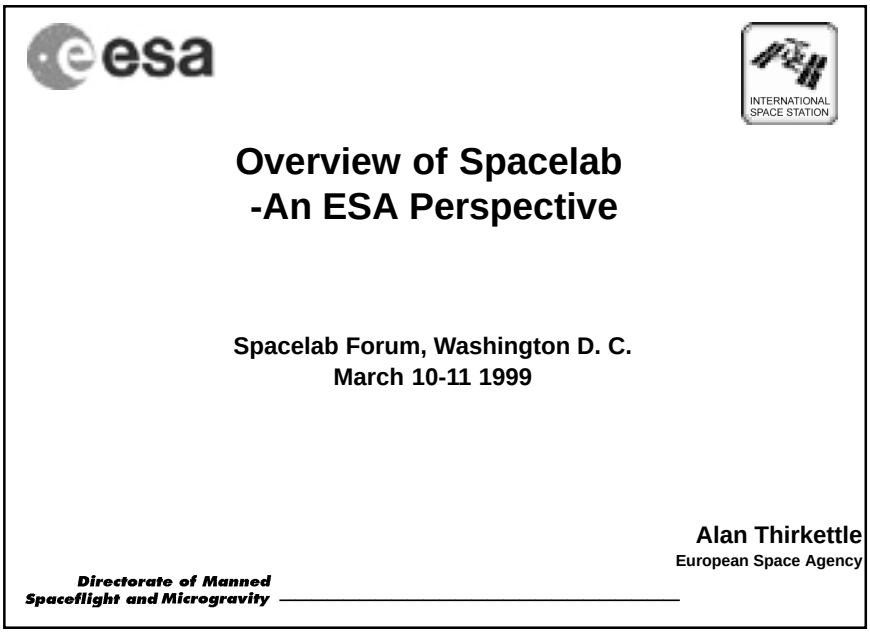


Figure 1. Introduction.

This is probably the most famous picture that exists of the Spacelab (Figure 2)**.** We like it because it shows the European ESA logo on the front of it.

Spacelab was born out of post-Apollo activities (Figure 3). The early 1970s saw a number of different options, attempts at international cooperation, including work on the Space Tug, including work on the Orbiter, and on a strangely named thing called the "Sortie Can."

Eventually, in 1973, NASA and a now nonexistent organization called the European Space Research Organization, ESRO, which today is ESA, agreed on a successor to the Sortie Can, which was called Spacelab.

The European role would be to develop and deliver a modular Spacelab system that was capable of providing both pressurized and unpressurized platforms. NASA would operate the system (if ever it was delivered), would purchase a second one — which was good news for us — would perform all of the flight operations, and, of course, would make the Shuttle itself available as the carrier vehicle for Spacelab.

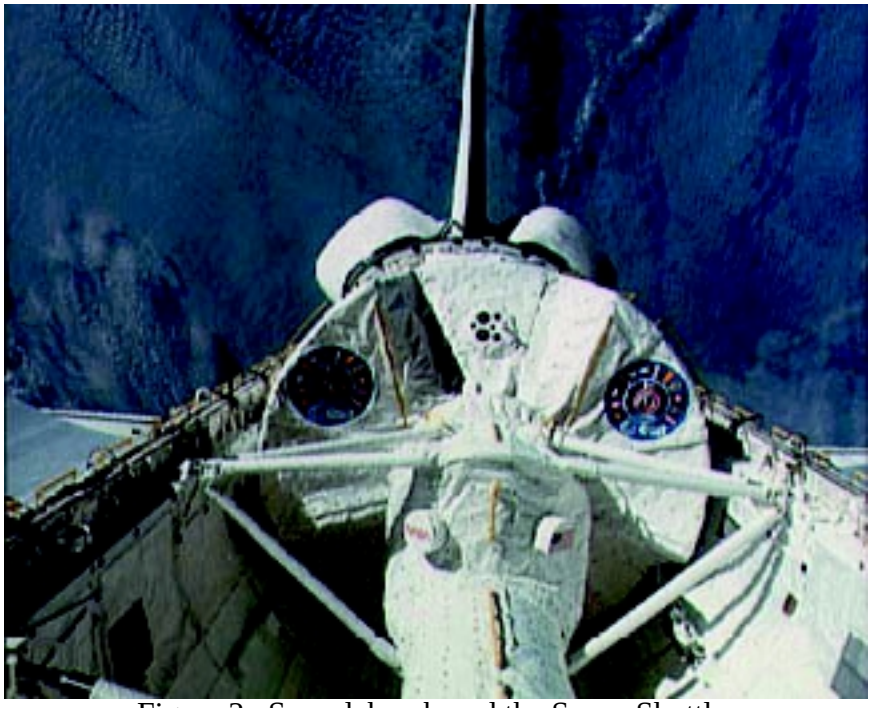


Figure 2. Spacelab onboard the Space Shuttle.

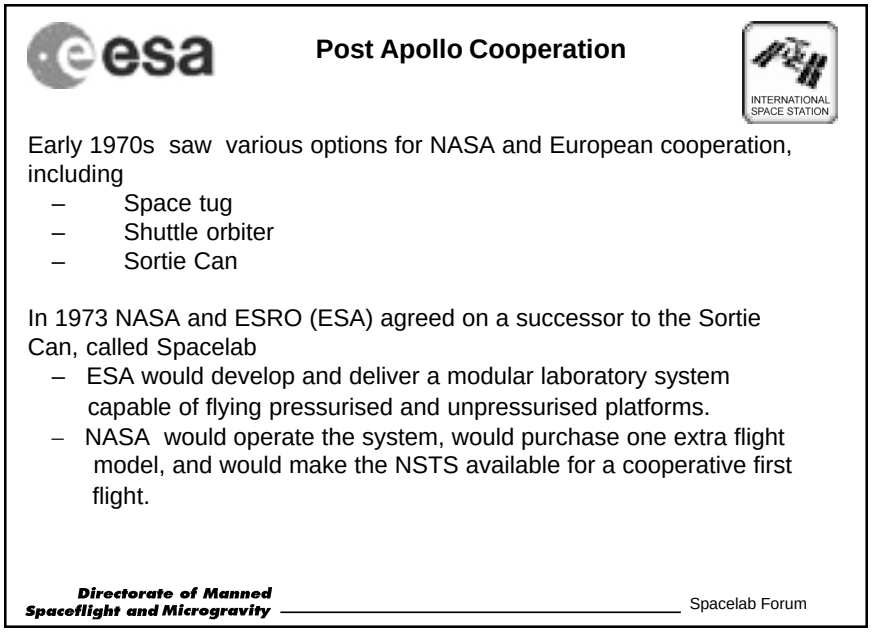


Figure 3. Post Apollo cooperation.

This was really a very significant move for the European aerospace world (Figure 4). Although we were, of course, well experienced in aircraft technology, we were very embryonic in space, and we had never ever worked on manned space before.

ESRO was a research organization that had previously built some sophisticated but relatively small satellites, and both the agency, and (even more importantly) its industry, were faced with this whole new chal-

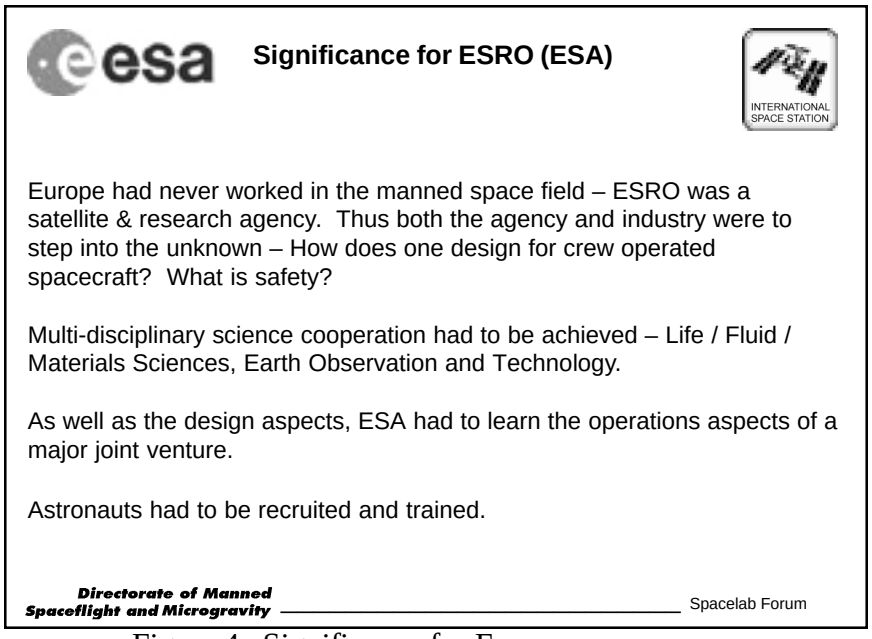


Figure 4. Significance for European aerospace.

lenge, a real step into the unknown. We started coming up against things like safety and habitability, and the whims and fancies of crew members. This was quite a learning curve.

The previous speakers have mentioned that this was meant to be a multidisciplinary facility, and indeed it was. But the organization of how to marry those disciplines, how to merge them, how to make them work together and not fight one another was also something that was quite difficult to do.

As well as designing Spacelab, we also had to learn how to support the operations of the laboratory itself and the operations, more importantly, of the payloads. Certainly, over the years, an awful lot of work went into the operations field and, as I will mention at the end, it is paying off in the way in which we are participating in the ISS today.

The final step that we had to take into the unknown was to advertise for, select, and recruit some astronauts. This was not a negligible task. First, there were 2,000 applications, and getting that down to three or four was quite an exercise in itself. It was of considerable significance for the whole field of aerospace research in Europe and was a major venture as far as we were concerned.

Being an agency/bureaucracy, of course we had to have an organization in place to look after this (Figure 5). Being more than one agency, ESA and NASA, you can imagine the degree of boards and committees and panels and everything else that we managed to set up. All of them seemed to have their own unique role, their own unique task, and were all brought together in a way that today, in retrospect, looks to have been quite efficient.

Back home at ESA, we established basically three different strata of management. Firstly a program oversight level, which in common with all our programs, was carried out from the ESA headquarters in Paris. The project level management was allocated to the technology center of the agency, ESTEC, at Noordwijk in Holland. The payloads and utilization activities, from a paper point of view, were shared between Paris

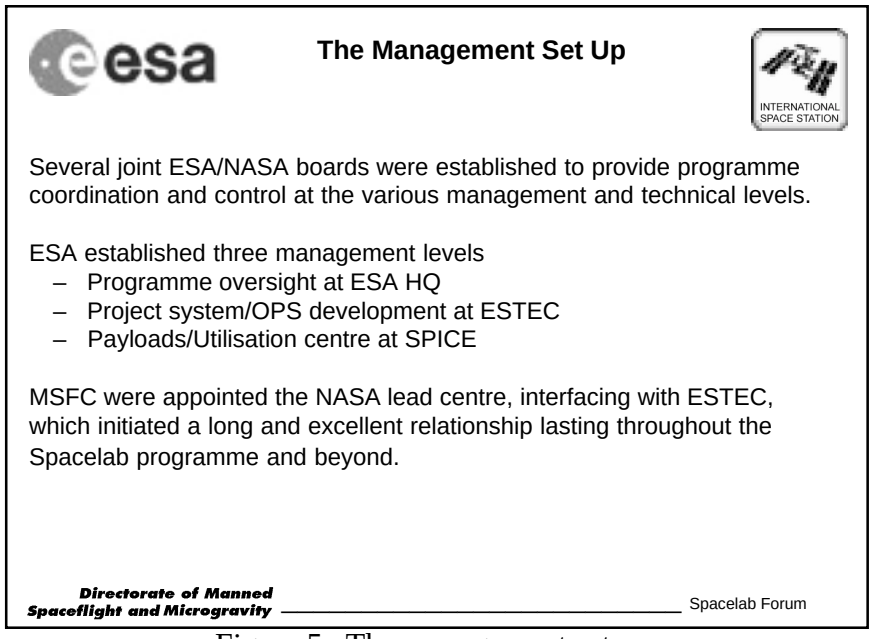


Figure 5. The management set up.

and ESTEC, but from a hardware implementation and an operations point of view, were centered initially within an organization called SPICE, the Spacelab Payload Integration Center in Europe, located at Portswahn in Germany.

Marshall Space Flight Center was given the task of being the NASA lead center as far as the development was concerned, therefore interfacing with the team at ESTEC. I must say that led to one of the greatest spin-offs that this program has had, and that is the relationship that was built up between the Marshall Space Flight Center and ESTEC and the rest of the European scene. A relationship which became a genuine mutual respect and admiration for one another. It was a terrific cooperative venture between the two. Those relationships still exist today, and they are active today, and they are productive today, and I think that was a major facet of the cooperation.

Enough of agencies and things. The people that really have to do the work are in industry, at least in Europe. An industrial consortium was set up led by the prime contractor, which was the ERNO Company (Figure 6). They are now part of the Daimler-Chrysler Aerospace, the DASA organization. ERNO won the right to be prime after a competitive proposal phase.

I have a historical chart of the consortium (Figure 7). Believe it or not, every one of those is a company, or was a company. They each had different responsibilities, different tasks, different work packages. They each had a subcontract. Poor Klaus Berge had to negotiate all of the subcontracts that you can see on there. I'm not sure if he has finished them yet.

Many of the companies that are listed there don't exist as commercial entities today. Starting from the top, it was ERNO when it was started; it then became MBB ERNO. It now is a part of DASA. Various subsystems were set up; various equipment suppliers were set up. I guess half of those companies all belong to one company today, but it was an enormous consortium. It had to represent all of the participat-

The Development Set Up

An industrial consortium, led by ERNO (now part of DASA) was selected after competition.

The consortium represented all participating ESA member states, Germany being the leading “shareholder”.

A project team was established at ESTEC with staff drawn from satellites, aircraft, US manned space contractor experience, etc.

The ESA/ERNO task – to develop a modular vehicle capable of 50 separate two week flights in the orbiter, within a fixed budget of 308 MAU (in 1973 prices) – about $1 billion today.

Figure 6. The development team.

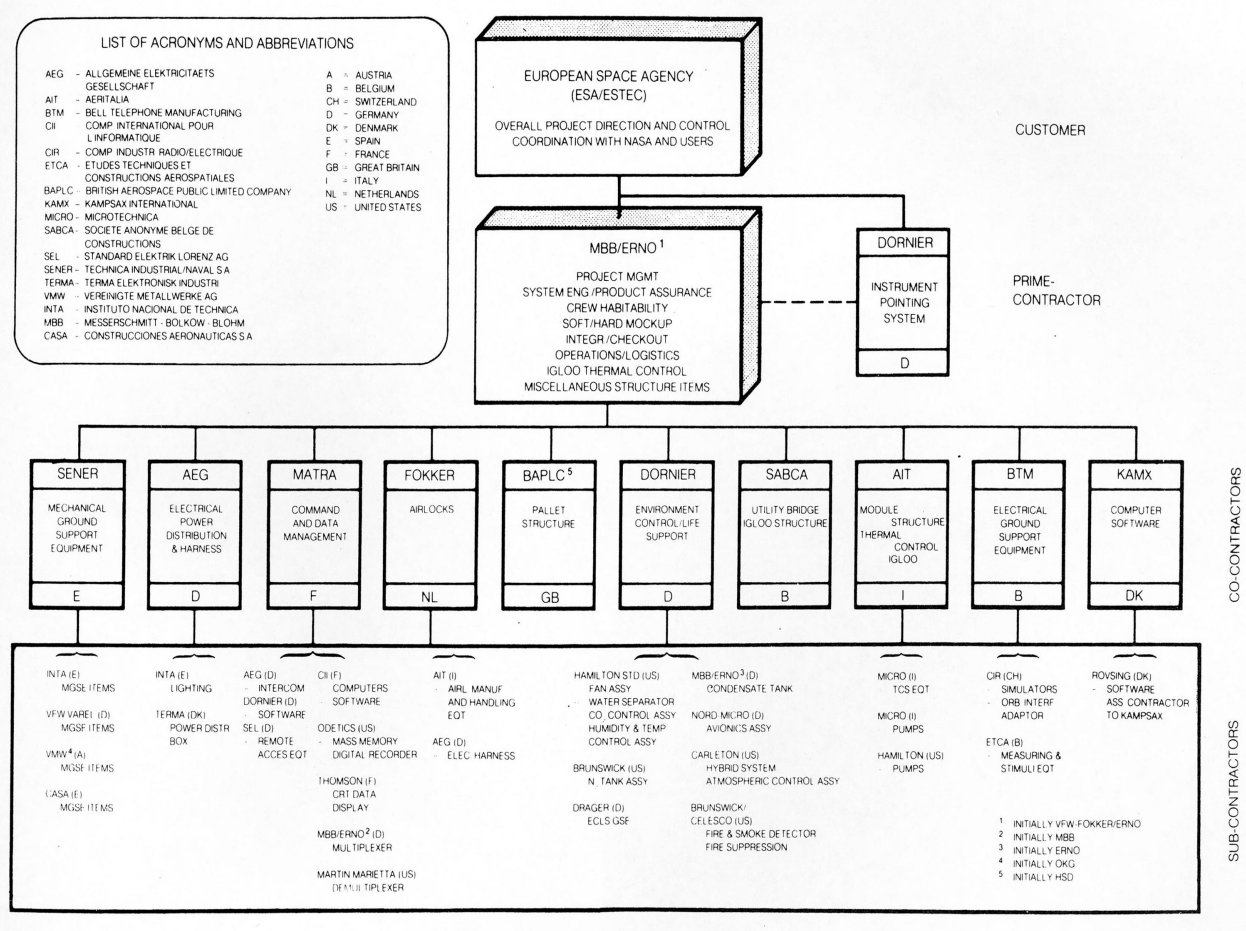


Figure 7. Historical background of Spacelab European Development group.

ing member states of the contributors to the financing of the Spacelab and was led by ERNO as a result of Germany being the major shareholder in the program for Europe.

We established a project team also at ESA because we wanted to watch what the heck these people were doing with our money. That team was drawn from satellite areas, from aircraft areas within Europe. We also raided the American companies to find anybody that had a European passport, that had any experience on manned spacecraft at all. They came and joined us. We fished a guy from a U.S. Navy aircraft because he was going to be our ergonomist. Anywhere we could get people, we got them. They were led by Heinz Stoewer, who put together a team that was, to say the least, diverse.

The task of ESA and ERNO was to develop this modular vehicle. It was meant to fly 50 times — it got close. Fifty, 2-week flights within the Orbiter. We were given a budget of 300 million accounting units in 1973 economic terms. (That will not mean a lot to you. It's roughly a billion dollars in today's money.)

We had to produce a number of configurations (Figure 8). Three particular configurations were used as reference configurations: the long module plus one pallet; a "three separate pallet" train; and "a two plus three pallet" train. These were selected as being the reference for mass, for power, et cetera, et cetera.

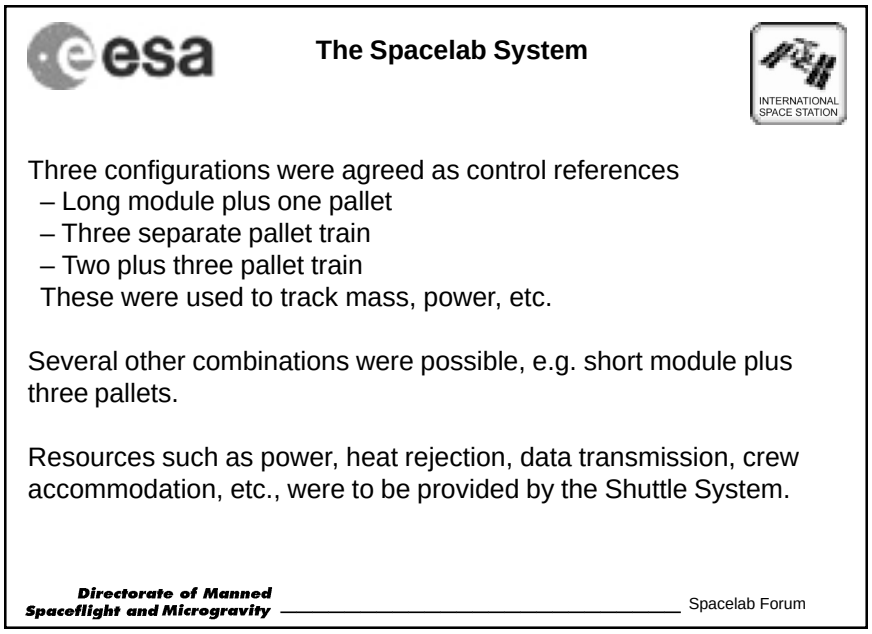


Figure 8. The Spacelab system.

But a number of other configurations and combinations were possible**:** a short module and three pallets, the top left-hand corner, for instance; long module and two pallets; long module only. A number of different configurations were there (Figure 9).

That was fun from an engineering point of view. It's a total disaster from a configuration management point of view. It was really very, very difficult to get our arms around this. It was another technology that we learned how to handle.

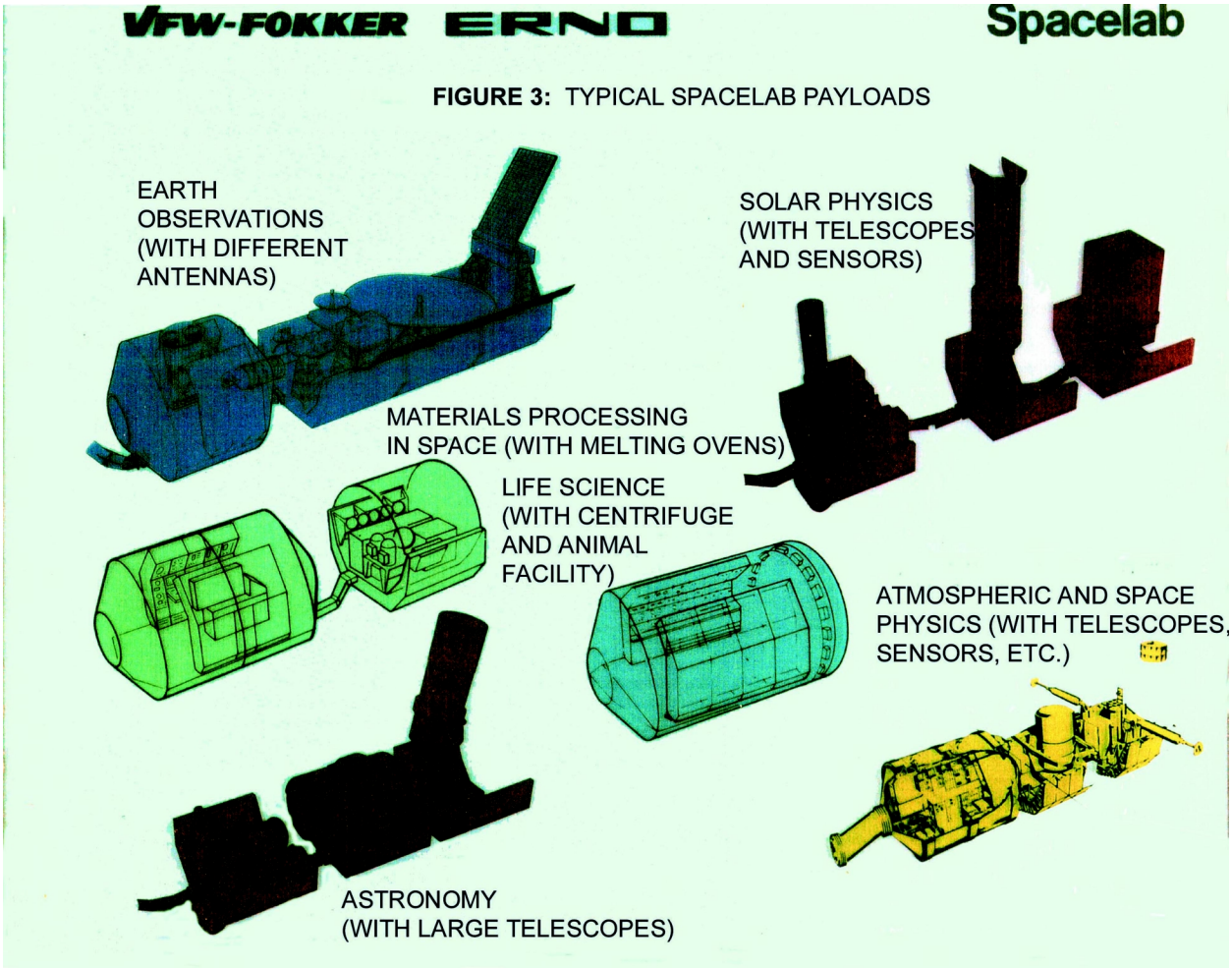


Figure 9. Sample Spacelab configurations.

The resources themselves, the power, the heat rejection, the data transmission, crew accommodation, their sleeping quarters, et cetera, were all provided by the Orbiter. Spacelab and Orbiter were really part of an integrated system, the Shuttle system, and very closely interrelated with one another, with NASA providing the tunnel between the Orbiter aft flight deck and the module itself.

Not only did we produce a module, the racks inside it and the pallets, there were a number of other elements as well (Figure 10). There were mission-dependent elements, the scientific airlock being the obvious example. If the user community wanted to fly an airlock, they could have it; if they didn't want it for a particular mission, then they didn't need to fly it. Viewports were available if general observation was necessary. An optical window was provided. In fact, we used the spare glass out of the Skylab program. Of course, the biggest of all of these things was the Instrument Pointing System, an extremely sophisticated, extremely accurate pointing system capable of operating a telescope of up to three tons.

Indeed, the Spacelab itself lived inside the Orbiter. The Orbiter was under development, as has already been mentioned. So, here was a laboratory being designed by a bunch of aliens and an Orbiter being designed by a bunch of Californians. We had to try and make sure these things would fit together, and the famous Interface Control Documents were invented, were created, largely, I believe, from the initiative of

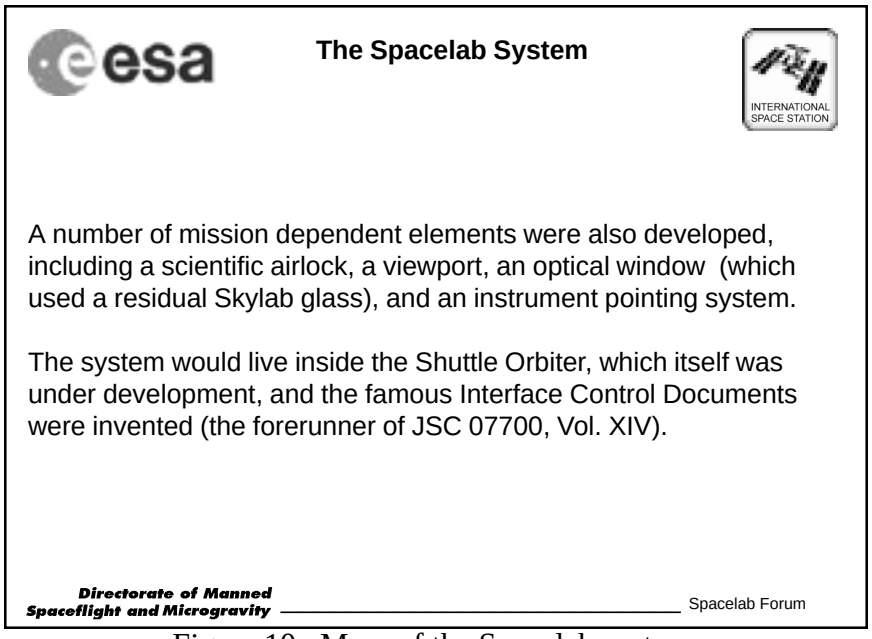


Figure 10. More of the Spacelab system.

MSFC. They became the forerunners of JSC 07700, Volume XIV, which is the Bible if you want to fly inside an Orbiter these days.

That is a picture of Hall 41, so-called in Bremen, the prime contractor site (Figure 11). On the left-hand side is the engineering model; the right-hand side is the flight unit under construction. This picture must have been taken in the late 1970s or early 1980s You can see in the foreground all the ground support equipment. We had to try to simulate the Orbiter, simulate payloads, and hook them up to Spacelab to check it out. You can see it was quite a busy area to work in. It was a place where a lot of people lived for a long period of time.

A list of major events is shown in Figure 12. We did our thing in Europe over a large number of years.

The first main delivery to NASA was the engineering model and the associated GSE, which was transported to Kennedy Space Center in a C5A-Galaxy and a 747 in December of 1980. The first flight unit followed a year after that, and the second flight unit a further year after that. The Instrument Pointing System was delivered in 1984, and what was called the follow-on production, the unit that NASA bought, in years subsequent to that.

This is a photo of the C5A on the Shuttle landing strip (Figure 13). Spacelab used the Shuttle landing strip before the Shuttle did. It came in on this C5A. It was a freezing cold day even though it was Florida. It was little bit like today. No snow, but it was below 32 degrees. All of the KSC people were totally frozen. It was only Europeans that had their fur skin coats on and were quite comfortable in this.

On the next chart are some of the highlights of what happened after the vehicle arrived (Figure 14). Whilst we had been developing the laboratory itself, the SPICE organization had been busy putting together the European part of the first payloads. Spacelab-1 was sort of a 50/50 ESA and NASA utilization mission.

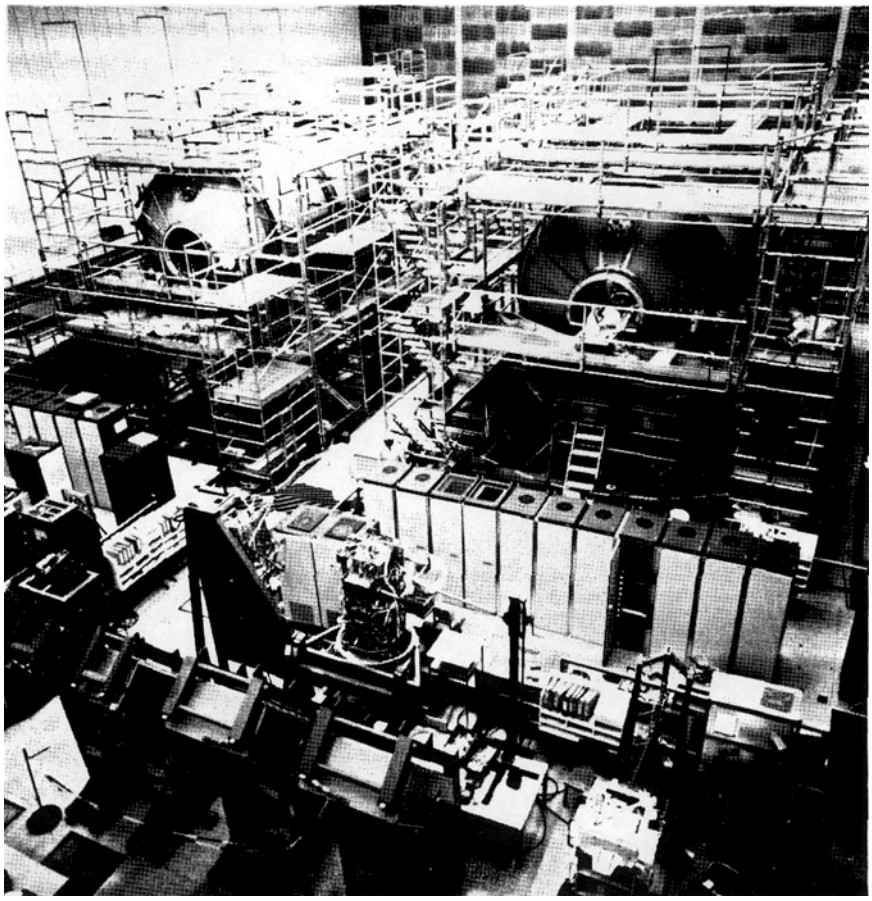


Figure 11. Hall 41, Bremen.

esa

The Major Events

INTERNATIONAL SPACE STATION

The first main delivery was the engineering model and the GSE SET 1, which was transported to KSC from Bremen in a USAF C5A and a Lufthansa Boeing 747 in December 1980.

The first flight unit – a long module and one pallet – was delivered at the end of 1981.

The second flight unit – an igloo, some pallets and yet more GSE, followed at the end of 1982.

The Instrument Pointing System followed in 1984.

Figure 12. Major events in Spacelab development.

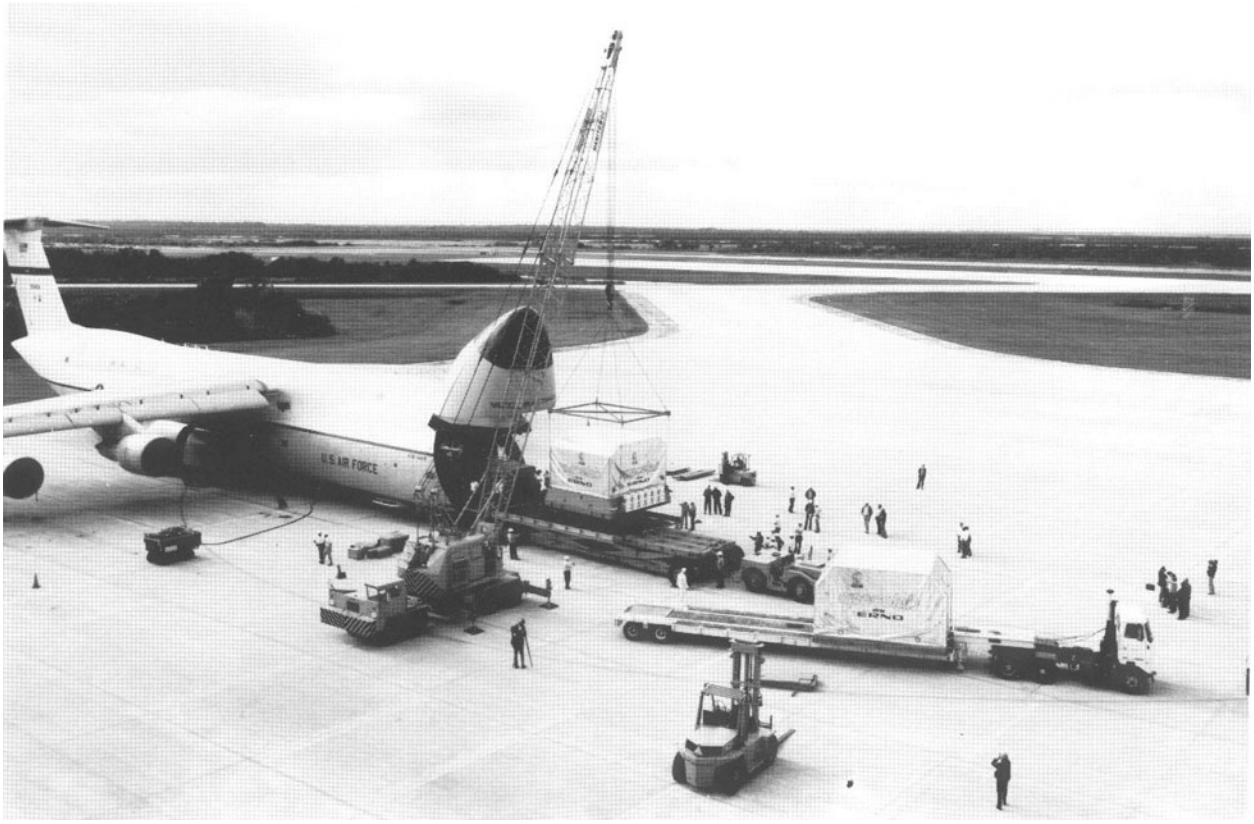


Figure 13. C5A delivering Spacelab to Kennedy Space Center.

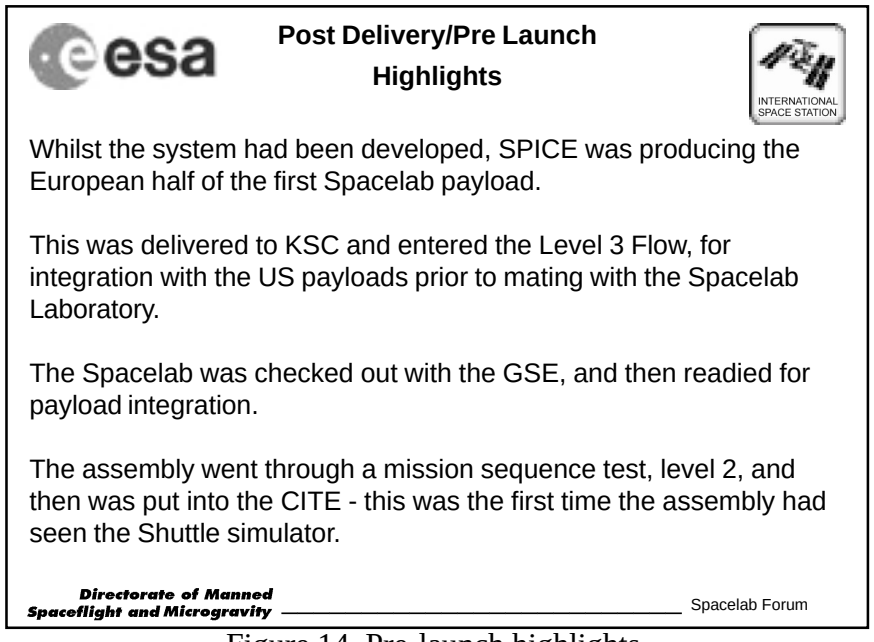


Figure 14. Pre-launch highlights.

SPICE was responsible for the integration of the European part of the payload. Those payloads were delivered to Kennedy and entered the so-called “Level 3 flow.” In a minute, I will show you a chart of all the different flow stages.

There they were integrated with the U.S. payloads, checked out as a complete set of payloads, and then brought to the Spacelab, which itself had been checked out as a laboratory. We had to integrate the payloads with the Spacelab. That created Level 2. Then, the entirety was itself checked out before then being checked out against the Shuttle equipment.

We went through a mission sequence test to see if we could, in fact, operate this entire thing. Then, we put ourselves through the CITE, the Cargo Integration and Test Equipment, which was a Shuttle simulator. That was the first time that Spacelab had ever seen that Shuttle simulator.

The next chart is a cartoon of what was meant to be the typical flow (Figure 15). You have to try to start at four o'clock on this chart. Let's pretend that we have just flown a mission and we disassembled the thing. The flow takes you through Level 4, which is where the racks were integrated with the particular payloads and all the pallets were integrated with the payloads, and then were brought together as a rack set (seven o'clock) in an experiment train. That was the Level 3 exercise.

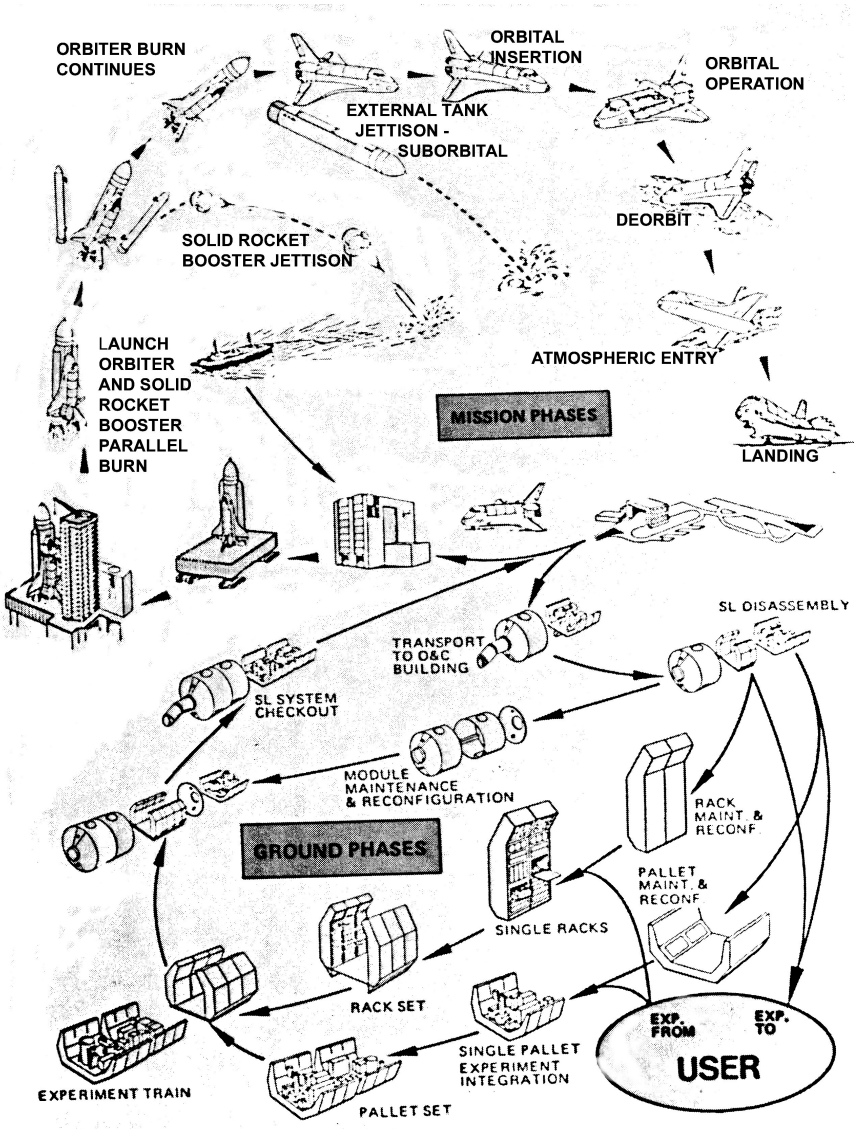


Figure 15. Spacelab flow chart.

That train was put into the Spacelab assembly (eight o'clock), went through Spacelab system checkout, the Level 2 activities, and then the Spacelab was taken to the Orbiter out in the Orbiter Processing Facility (OPF); it was integrated with the Orbiter, and was launched. The thing would do its two weeks on orbit and would land back down again on the landing strip. Spacelab would be taken outside of the Shuttle in the OPF, and the various bits and pieces returned to the various stages of the flow for the next mission. The viewgraph was quicker to draw than the tasks were to perform, I can promise you.

The next picture gives a little bit of a flavor of what the previous view chart turned out to mean in terms of hardware movement (Figure 16). This is a picture of the Operations and Checkout (O&C) Building at Kennedy Space Center (KSC) where you see the integrated rack train of Spacelab-1 that had just finished going through its testing against its own electrical ground support equipment (EGSE), utilizing simulators of the Spacelab. It is moving over the pallets, which you see in the next stand immediately behind it, toward the empty Spacelab module, which is waiting for that experiment train to be integrated into it.

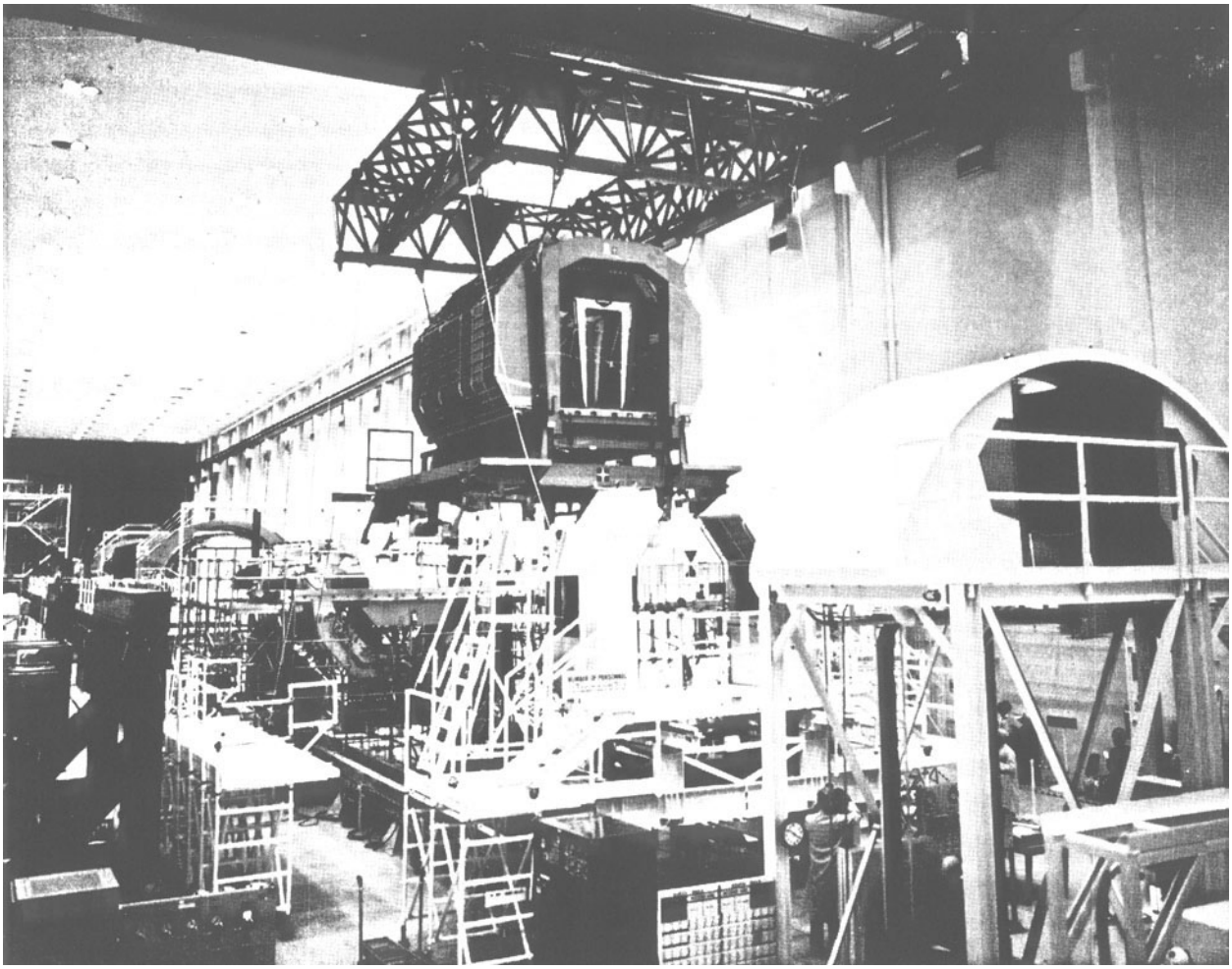


Figure 16. Hardware integration in the O&C building.

Here is a picture of what it looked like to work inside that module (Figure 17). This is archival stuff. This is the performance of integrated payload and Spacelab testing, again in the O&C building, before the flight, I hasten to add. This isn't on orbit. You can see the kind of activities that were going on in there. This whole complexity is being operated by three guys on the end of earphones that were connected to the

checkout rooms. It was some fun activities that were done there. Not everything was plain sailing. Believe it or not, we had some problems.

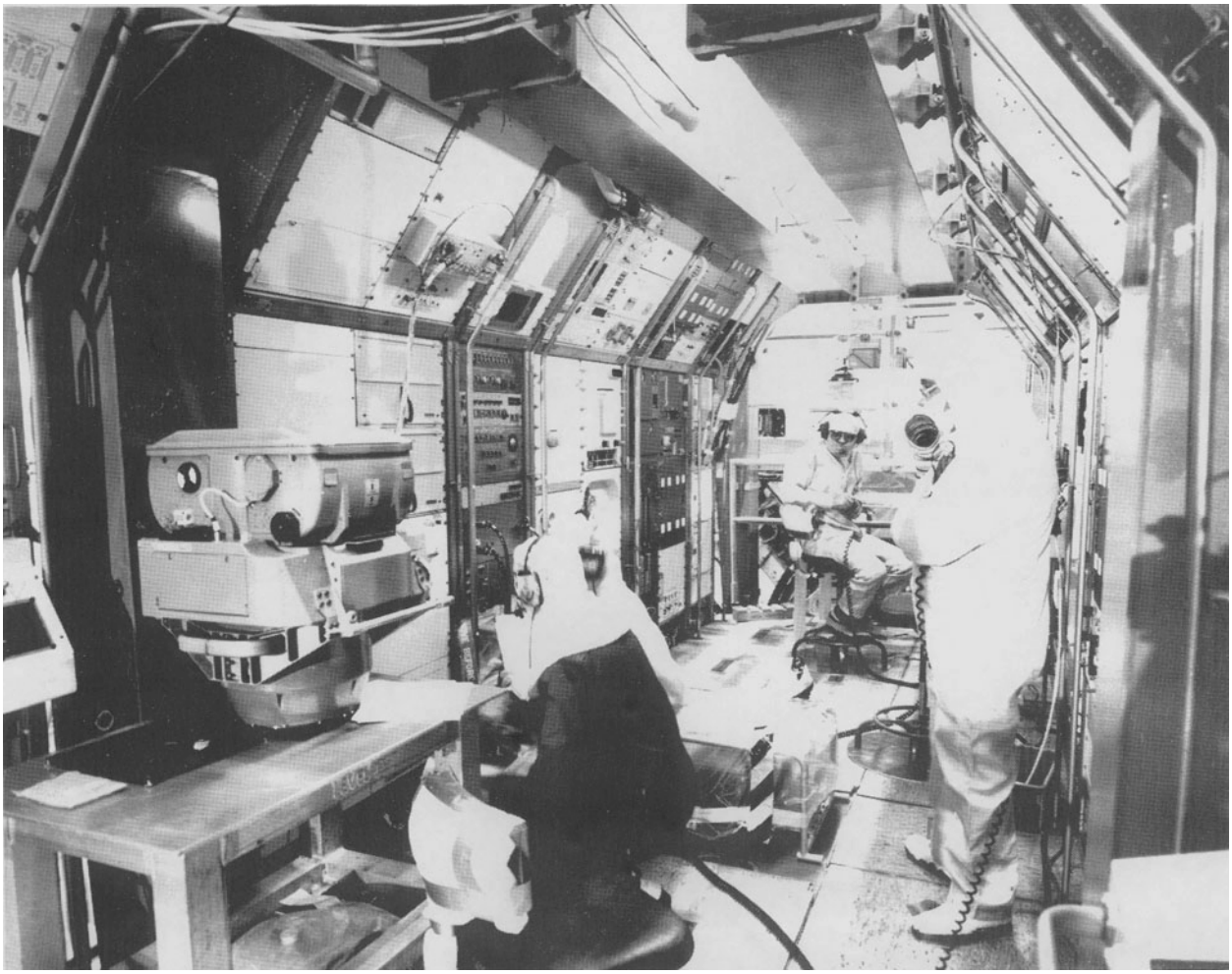


Figure 17. Inside the Spacelab Module, pre-launch.

Particular things had to be done just a few months before the first flight (Figure 18). The Spacelab flight unit computers and high-rate multiplexer were both found to have design faults. These were things that we had seen in Bremen, but in the anxiety to get Spacelab delivered maybe we weren't clever enough in analyzing the problems that occurred. We thought we had little software work-arounds to these things, but, in fact, they were basic design problems in the computers.

We had to get the things removed, redesigned, repaired, replaced, and back into the flow. We had six weeks in which to do this, and those six weeks included Christmas and the New Year. I think one of the real achievements of the industrial support was to fix that problem without a single day of slippage in the ground processing flow. It was a fun Christmas.

After we had been through the Cargo Integration Test Equipment (CITE) integration, the simulation with the Shuttle, we actually went into the Shuttle itself. Of course, we wanted to do a power up inside the

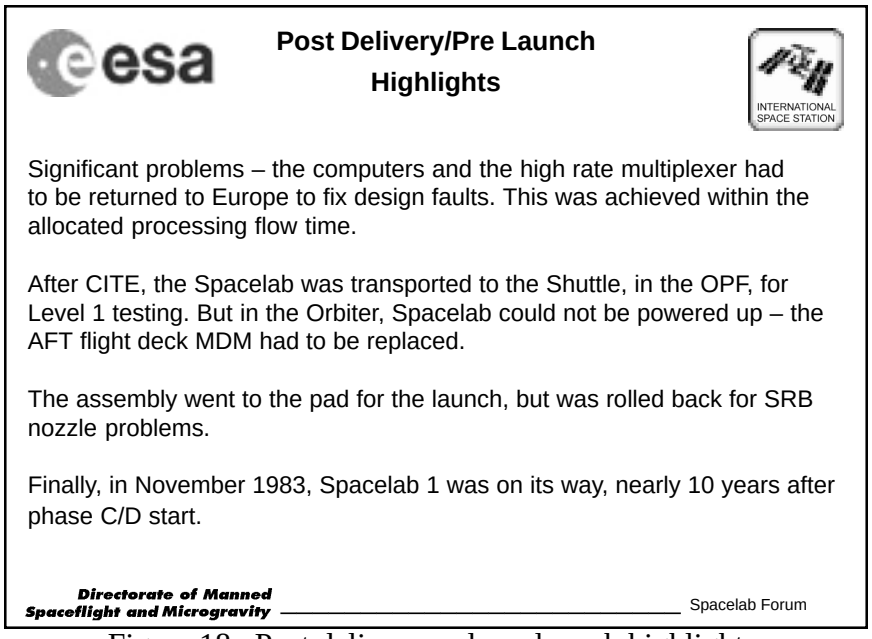


Figure 18. Post delivery and pre-launch highlights.

Shuttle to make sure everything was okay. Unfortunately, the electrons wouldn't go from America to Europe in that configuration. We spent three or four days finding out that the Shuttle multiplexer-demultiplexers (MDMs) had been connected up to the their test port rather than to the real port. It took us three days to find that. I remember Spacelab was being accused by a NASA guy of being a terrible piece of ground support equipment (GSE) to check out the problems with the Orbiter, but we found the problem and got it fixed!

I thought that I would show a nice pretty picture of the Spacelab going inside the Orbiter, in the OPF (Figure 19). This thing down here that looks like the back of a theater stage is, in fact, the payload bay of the Orbiter. We had to get lowered down into that thing.

Eventually, we went out to the pad. We were now getting quite excited. We were going to get ready for launch, but then someone found out that the solid rocket booster (SRB) nozzles were no good and we had to roll back again, which was another couple of months of delay.

Finally, in November of 1983, Spacelab-1 was launched — almost ten years after the start of the phase C/D. Here is the happy moment of liftoff at 11 o'clock in the morning on a November day, right on the button (Figure 20). The countdown was totally flawless. It was a huge relief after what we had been through. It was a very nice day indeed.

The first mission itself lasted from the 28th of November until the 8th of December (Figure 21). We landed a day late for all the right reasons. The onboard system was incredible. By system, I mean the Orbiter plus Spacelab. The launch parameters were well below the design limits. We had worried about launch loads; we had worried about acoustics. None of those things were problems.

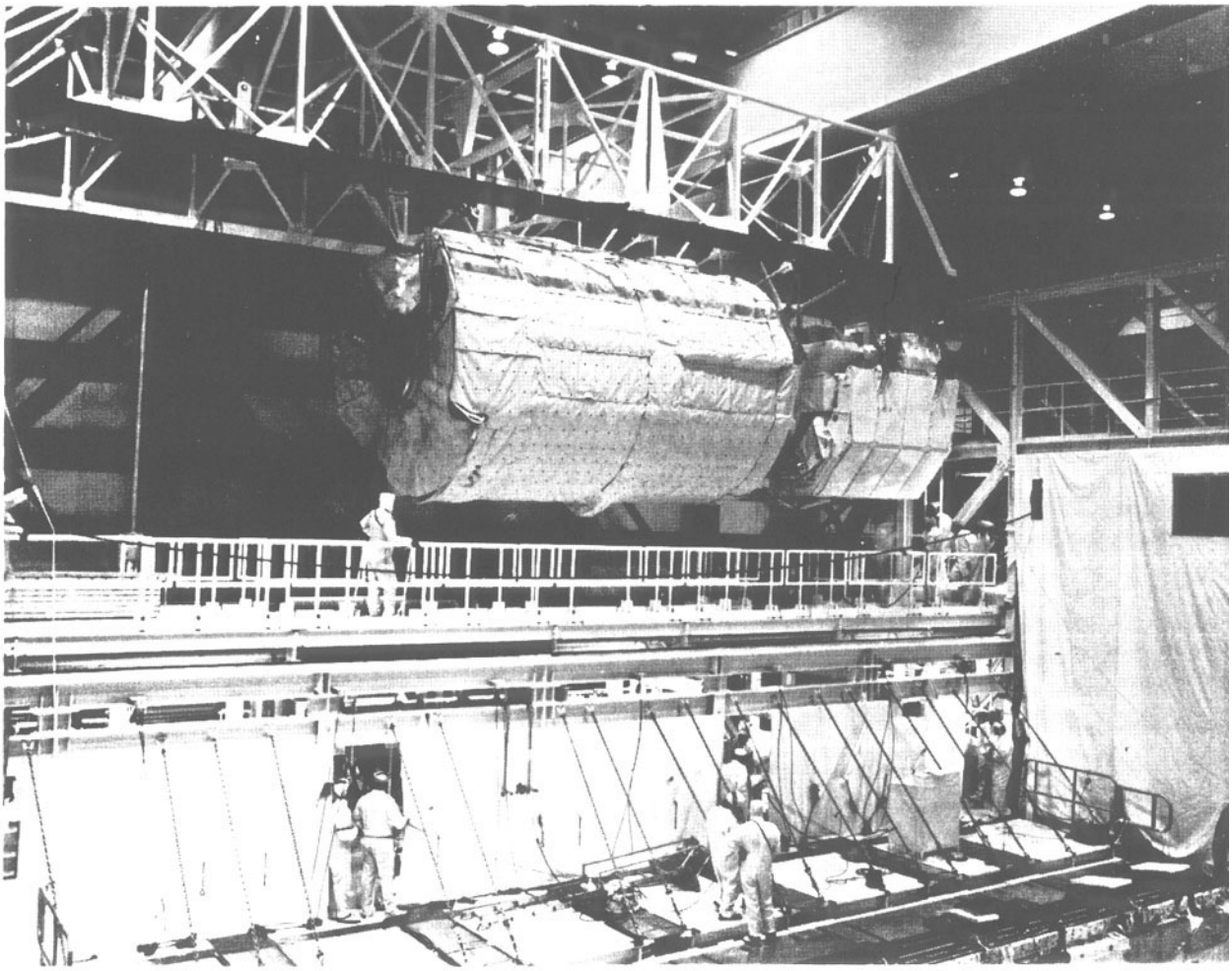


Figure 19. Spacelab being placed into the Orbiter at the OPF.

Spacelab consumed one kilowatt less power than on paper it was predicted to do. That meant that the fuel cells had a lot more margin and that was one reason why we spent an extra day on orbit. We were able to get an extra day of payload operations as a result of that.

The data communications, the team at White Sands, and I don't know what else in the link, all worked beautifully all the way through.

We had no atmospheric leakage. In fact, we had a problem with the pressure inside the vehicle. In Huntsville, the telemetry was telling us that the pressure inside the Spacelab was about 0.1 psi greater than the pressure inside the flight deck of the Orbiter, which was a bit tricky because the hatches were open. It was part of the international cooperation. They were working on pounds per square inch up there and we were working in metric units. The conversion said that the two vehicles were operating at different pressures. That occupied one night shift during the mission, quite happily.

We had lower carbon dioxide (CO_2) absorption than we expected. That was also good. That meant the crew didn't have to spend a lot of time hanging out the lithium hydroxide (LiOH) canisters.



Figure 20. Launch of Spacelab-1.

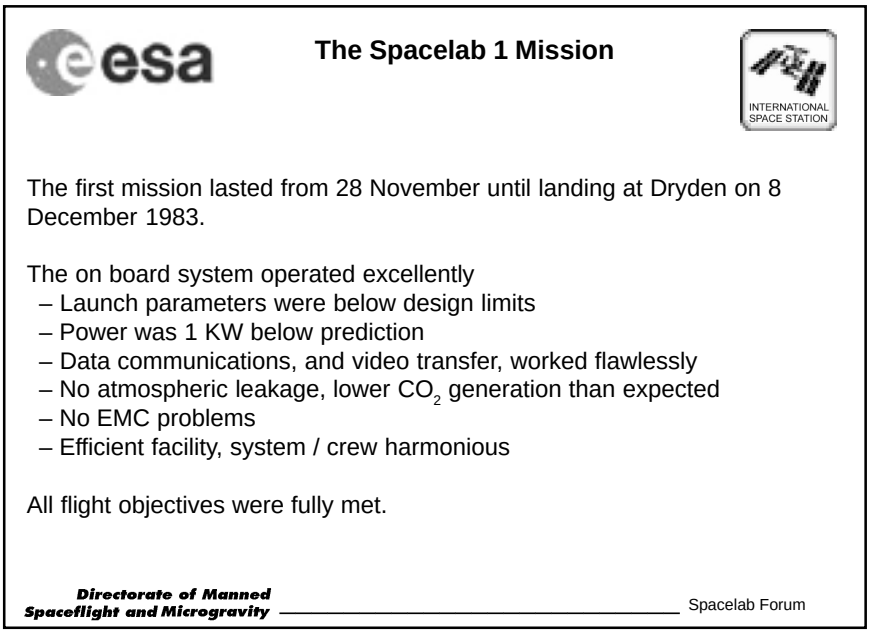


Figure 21. Spacelab-1 highlights.

We had absolutely no electromagnetic compatibility (EMC) problems. This was a piece of black magic that we were worried about throughout the entire program. We had been concerned that, as soon as you switched on the payload from some university, the receivers of some one else's payload would go off because of the spikes. There was absolutely nothing. It was crystal clean, the whole mission.

The operation between the ground and the orbit, and the whole operation of the facility was very, very smooth indeed. The Europeans, the Americans, the Payload Operations Control Center (POCC) at the Marshall Space Flight Center (MSFC) where the payloads were operating, the Johnson Space Center (JSC) Control Center, the crew on board, everything was very, very harmonious, as much as these things ever are. There were one or two little bits of problems with the crew, but one has to take those things as a norm!

All of the flight objectives were totally met. It was a very successful mission. For such a complex and such an innovative thing, it was quite an achievement.

On the mission itself, there will be far better people than me qualified to talk about it, and I am sure they will do that (Figure 22). There were 70 separate experiments that were flown. Nearly everyone obtained the required data. There were a couple of experiments that had some problems, but out of 70, virtually all of them got the data.



Figure 22. Spacelab-1 mission highlights.

The flight crew and the ground crew performance was truly outstanding. (And that's a European "outstanding" — not an easily said "outstanding".) It was excellent. There were very few anomalies, but there were anomalies. They had to be fixed, and they were fixed in real time. That, again, took a lot of interactive work between the ground and the onboard crew. It was a joy to participate in that thing.

The POCC at MSFC; the European User Centres. This is another piece of technology I've tried very carefully to reflect on the charts. One uses "center" with an "er" for all the American ones and with an "re" for all the European ones. It's another metric conversation factor.

Even though we have to spell things differently, we manage to work together very well indeed. It was a 24-hour-a-day operation, of course, compared to the 72 man-hours per day of on-orbit crew. For Columbus, we get shall get two crew hours a day, 72 hours a day for Spacelab.

There were some problems with the Orbiter that were unique for this mission. There were the famous big bangs. I don't know if anybody here has heard about them, but there was apparently some form of friction problem between the trunnions of Spacelab and the Orbiter payload bay, and in certain thermal environments there was a real thump of a noise. We were led to believe from the crew afterwards that this would have exercised quite considerably the laundry facility of the Orbiter if there had been one.

During the reentry, there were some very nasty problems with the Orbiter computer and inertial measurement units (IMUs). They were without navigation for a couple of orbits just before reentry, which was tricky, but again, the problems had to be fixed, and were fixed.

It is not an exaggeration to say that overall the mission was a huge success for ESA and also for NASA. I think, most importantly of all, for all of the users that had waited so patiently to participate and get their data.

There were some further involvements from Europe after Spacelab-1, of course, notably Spacelab 2 and 3 and even more notably, the German D1 and D2 missions (Figure 23). They were most significant because the payloads were operated from the German operations control centre, which is the forerunner of what we are going to do as far as the Space Station operations are concerned from Europe.

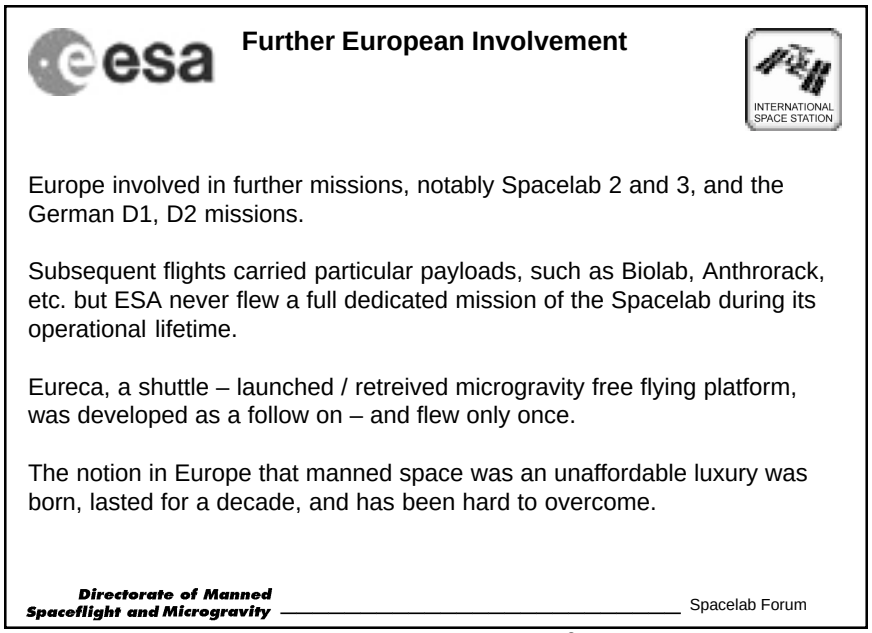


Figure 23. European involvement after Spacelab-1.

There were subsequent flights where Europe was involved in carrying particular payloads, Biolab, Anthrorack, and a number of things like that, but ESA never again flew a dedicated mission during the operational lifetime. As somebody that worked on the development of the thing, that for me was a big disappointment. We never followed through on a utilization program in the fundamental way that we had intended when we first started this program.

We developed a retrievable carrier as an offshoot of the Spacelab program called EURECA, a microgravity free flyer. That was flown very successfully once. It was meant to be a reusable spacecraft, but again, it only flew once and we didn't use it.

During the period of time after the first flight of Spacelab, the notion - it's a mild word - in Europe was that manned space was just an unaffordable luxury. This notion was born and lasted for a very long period of time. This has been extremely difficult to overcome, extremely difficult. I think that we start to see the light at the end of the tunnel on this now, but there is a difficult heritage for us to overcome in terms of lack of enthusiasm for utilization.

So, we moved to the "link to the future" (Figure 24). As I said, for ten years we could just not get our various governments to follow up on manned space and to participate in the logical conclusion of Spacelab, which is the Space Station.

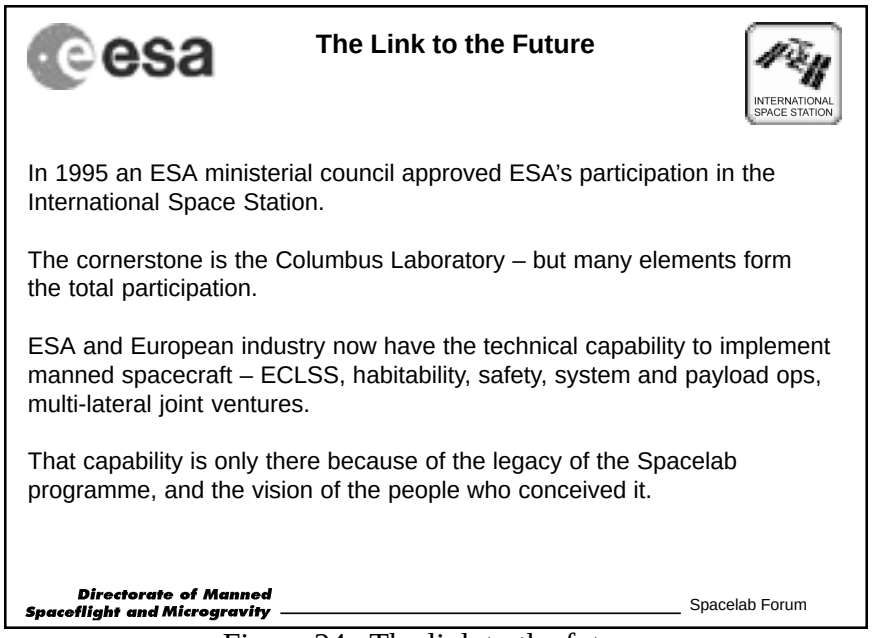


Figure 24. The link to the future.

Finally, in 1995, a ministerial council approved our participation in the International Space Station, the cornerstone of which is the Columbus Laboratory, which in terms of size and overall appearance is very, very similar to Spacelab.

We have many elements involved in the participation of the Station itself. This is a rather parochial chart that shows where Europe is on the Space Station (Figure 25). About four o'clock you see the Columbus module. That is our laboratory, and that is the cornerstone.

At nine o'clock on the chart is the ATV, the automated transfer vehicle, a logistics vehicle which will make flights about every 15 months or so to the Station and upload about nine tons of logistics as our contribution to the common operations costs of the Station.

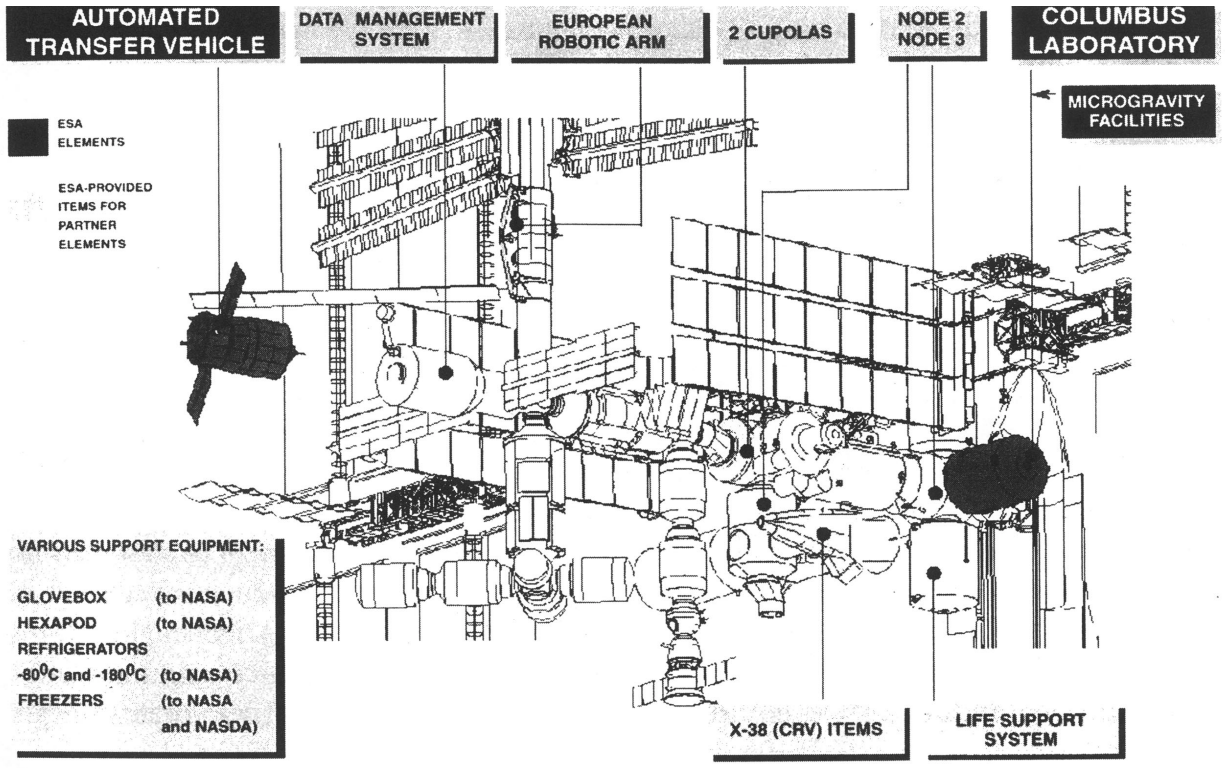


Figure 25. European involvement in the International Space Station.

We are building a European robotic arm that will operate from the Russian science and power platform, SPP, which you can see at about 12 o'clock there.

We are designing and developing nodes 2 and 3 in Europe. Node 1, of course, is Unity, which is up there now. It was built by Boeing, but we are producing nodes 2 and 3, which are a totally different design to node 1. As part of a barter arrangement with NASA, they launch Columbus for us; we pay for it with nodes 2 and 3 (plus a few other items).

We are responsible for the data management system of the Russian service module which is going up later this year. That data management system, of course, is the same as that system which will be used in Columbus and is used in the automated transfer vehicle (ATV) as well.

We are building a lot of facilities, some of them that go in the early part of the Station build-up: the glove box, the 80 degree freezer, and a pointing device called a hexapod. A number of these items will be launched in the next two or three years.

We are putting in a number of rack facilities that will go into Columbus and the U.S. Lab: microgravity facilities, biological facilities, various multidisciplinary facilities that will be there for the users to operate; cryo-freezers; participation in the Multipurpose Logistics Module (MPLM). We are all over the place!

One of the companies on the original Spacelab industrial organigram that I showed you was called Aeritalia. They are now today known as Alenia Aerospazio. They are building 14 modules for this Station. That is

more than anybody else is doing. They are building three MPLMs, the Multipurpose Logistics Modules. They are building the two nodes; they are building the structure of the Columbus module; and they are building the pressurized structures that head up the ATV logistics mission.

We now have the confidence, the industrial capability, and the technology to participate in this. We are a relatively minor player in the Station, but with what we are doing as a minor player, you get a feeling for the magnitude of this wonderful program that is going on at the moment.

We are happy and pleased and comfortable and confident to work in this. We have mastered the technologies of environmental control and life support (ECLS), of habitability, of safety, of system and payload operations, and of multilateral joint ventures of cooperation. We have done all of those things and we can participate in this.

There is only one reason for that, and that is because we did the Spacelab program. We would not be able to participate in the International Space Station (ISS) without the Spacelab program. I don't mean "we the agency" — agencies can do whatever they like — but European industry. They're the people that had to develop Spacelab, they did so and they are the ones who have developed this capability.

So it's the legacy of the Spacelab program that enables us to participate in ISS and therefore, of course, the vision of the people that created it in the first place, and that's why we are all here today.

I thank you very much for your attention and for the opportunity to present to you.

Building and Operating Spacelab – Spacelab Design and Systems Engineering Panel
Mr. Axel Roth, Panel Moderator

As you have heard this morning, I think we would be remiss in not talking about how this whole thing got put together and how it was operated to begin with.

I've got a fairly distinguished panel of people with me.

We are going to start off with Mr. Klaus Berge. Mr. Berge is now the Director of Space Project for the German Aerospace Center. Klaus was a former project manager at ERNO at the time, and I think you heard from Allan Thirkettle that it is now called DaimlerChrysler Aerospace (DASA). He was one of the early project managers of the Spacelab program.

I also have next to me Mr. Bob Benson. Bob is a former Director of the Flight Systems Division at NASA Headquarters, and he had a lot of things to do with Spacelab even in the very early days.

I have Mr. Allan Thirkettle, who was also introduced. I got to know Allan — I guess our first meeting was in the 1974-1975 time frame when Allan was the structural engineering manager for the Spacelab program, known as the European Space Research and Technology Centre (ESTEC) at that time.

Harry Craft is the vice president for information systems at COLSA, and, at this point in time, in Huntsville, Alabama. Harry was the first Spacelab-1 manager of some of the things you saw Allan talking about a little bit earlier. Harry was kind of the mission manager that pulled that thing together.

I do want to say just a couple of things about Spacelab that Allan and some of the other people have alluded to. I came to the Spacelab program in 1974, right after Skylab was finished. The last crew came off of Skylab, which I still consider as being the first space station that was ever put up.

It was kind of innovative to go from a Skylab program to the Spacelab program and dealing with the Europeans for the first time. At the same time we were developing the Shuttle Transportation System (STS) over here, they were an integral part to developing the Spacelab in Europe.

As Allan has mentioned, they had certainly not been involved in that size of a project and certainly not in the human space side. There were a lot of, you might say, cultural differences that we had to learn to overcome during that time. He alluded to some of them, even to the different spelling of words. We would get mixed up because instead of us putting a decimal point, they would put a comma. Those little things got us into trouble at times.

I think it was a great project. I'm not even sure it's still in publication, but Doug Lord, who was the first program manager at NASA Headquarters, after he retired put together a book that was called *Spacelab*. It

talks about the total history of it from the very beginning. Actually, the gleam of it started in late 1969. He goes through the whole history to the early flights in Spacelab.

I think it is a very interesting book. It gives a lot of insights. Doug always complains that when people read the book — at the end of each chapter he has insights, and that is where he tells some of the war stories — they seem to only read those, rather than reading the rest of the text. There are a lot of interesting things in there.

We were just talking a little bit earlier. I commented to some of the young people that always say, "well, you worked in the good old days." I keep telling them that the good old days are always 15 to 20 years ago. It doesn't make any difference where you are in your career. The good old days area is always 15 or 20 years ago. I told them, just think, 15 or 20 years from now you're going to be saying these are the good old days.

But I will have to say that in my 40 years with NASA and working on Apollo, Skylab, and various other programs, the Spacelab is something very unique. I think it was, indeed for me, probably the best part of my career. It was the most fun. The people, as Allan alluded to, I think are a very important thing. The contacts that were made that are still going on today. I think talking about Spacelab being a forerunner to the International Space Station (ISS) is exactly right because a lot of us that worked Spacelab are indeed working on the Space Station. I think it is for that reason that the Space Station is where it is today. Otherwise, I don't think it would be at the point it is.

Let me turn it over to Klaus, who will talk about some of the early days and his recollections from the European perspective of building and developing the Spacelab.

Mr. Klaus Berge

Ladies and gentlemen, it's a pleasure for me to be here. The story of the old times has two sides. One is the governmental side; one is the industrial side. Let me add, first, some remarks on the government side, which I did not belong to at that time but which I belong to now.

First of all, Spacelab represented the first joint European effort in manned space exploration through a general support capability to be flown in low orbit for a potential multidisciplinary user community. It was a far more expensive and complex enterprise than any previous one associated with the building of European satellites.

Secondly, but not less relevant, Spacelab was conceived as a major U.S.-European cooperative program concerning the development, procurement, and the use of the laboratory in conjunction with the Shuttle.

Furthermore, the Federal Republic of Germany, as the main contractor, and to a lesser degree the other European participants were eager to strengthen the industrial and technological links with the United States with regard to all aspects of such a new expertise to be extended from support capabilities for manned space exploration in low orbit to the Space Transportation System, or STS, as a whole.

After a decade of debates and recriminations on the technological gap between the United States and Europe, the time was ripe for Europe to be directly exposed through a common enterprise, through industrial savoir-faire, which seems to be embodied more in the organization and management of complex programs than in technical specifications.

Spacelab was, in fact, envisaged as an integral part of the U.S. program in the post-Apollo periods, and a major one. If we consider that in June 1972, when looking to the mission model for the period 1973 through 1986, NASA expected an average of twenty-five missions for the Shuttle per year and the same number of missions for the Department of Defense (DOD).

Among other missions, approximately eight per year would be sortie missions in the fields of life science, space technology, materials science, communication and navigation, Earth observation, astronomy, and space physics.

It is interesting to remember that, since that time, no more sortie missions were planned for the first three years after 1985, although the Space Station is supposed to accommodate experiments in those areas.

John Schumacher said that the U.S. Shuttle was approved in January 1972. The European Space Research Organization (ESRO) council approved the Spacelab program in February 1993.

The Intergovernmental Agreement (IGA) was drafted and approved. The Intergovernmental Agreement between the various nations participating within ESRO and the Spacelab, and the MOU between ESRO and NASA were born at that time, and it was again applied for the Space Station. At that time, on the industrial side, we started with Phase A and Phase B studies.

In 1970, the European Space Conference authorized the first studies related to the Space Transportation System. Also in those studies was the vision the Europeans had at that time to build part of the U.S. Space Shuttle. This, however, finally for political reasons, was rejected.

From June to November 1972, three European consortia, namely COSMOS, STAR and Mesh, concentrated on a modular orbital system to be flown by the Shuttle. They named it Sortie Laboratory or Space Laboratory and proceeded to three preliminary definition Phase A studies.

Afterwards, when it became clear that Germany would contribute more than 50 percent of the total cost of the sortie missions or the space laboratory, the further contracts for the Phase B, where we had several phases -- Phase B2, Phase B3 contracts -- were awarded to only two German companies, ERNO and MBB.

In early 1974, the ESRO project team at the European Space Research and Technology Centre (ESTEC) issued to industry a request for proposal for the design and development contracts, so-called Phase C/D. As a result of subsequent evaluation, the director general of ESRO recommended to the so-called administration and finance committee of ESRO the choice of the industrial consortium led by VFW-Fokker-ERNO against its rival MBB. I had the privilege for all those phases to be the proposal manager for the Mesh consortium, and I received that responsibility at the age of thirty-four years.

The reasons why VFW-Fokker-ERNO were chosen were, first, superior technical concept; second, the highest state of technical preparedness and depth of design for immediate implementation of Phase C/D; certainly greater suitability of concepts to user wishes; fourth, the particular strengths of top management aspects; and number five, the shortcomings of the proposal were more easily repairable both because of their nature and because some would come to be only later on in the project.

The price we proposed was about 180 million accounting units. At that time, the price in US-Dollars was about $350 million or $400 million. Within that price, we proposed about 30 percent in fixed price, which was really a surprise because everything was new. That was the start of the whole thing.

The first view of the Orbiter that we got from NASA was very round in many aspects, and the real Shuttle was certainly different later on. The “Sortie Can” version of Spacelab was divided in about three segments with two pallets. We began our understanding of what the Spacelab should finally be at that early time, and got a little closer later on. By then, the Spacelab had two segments and the racks inside. It was not really completed, and it looked very different later on. This, I guess, was a Phase B proposal. In the upper side of the module, on the left, was the air system to blow air into the module, and one of the consoles on the upper right.

On the distribution of tasks, we had a variety of subcontractors that we, as the prime, had to contract too. It started from Spain, over France, United Kingdom, Belgium, Netherlands, Germany, of course, Denmark, and Italy. There were other, smaller countries like Austria, and even Ireland.

Regarding the contribution in terms of percentage, ESA estimated it, at that time, at about 308 million accounting units - that’s a 100 percent reference. Fifty-three percent was from Germany; second was Italy; then Belgium; then France; and the other ones were much less.

To do this in this environment, our American friends, the Marshall Space Flight Center people, of which Jack Lee headed more than 100 people, could never believe we would be able to put that hardware together, managing a consortium all over Europe, with different cultures, with different education systems, and so forth. They only believed it when the first hardware, the pallet, which was the qualification pallet, was delivered to the United States and was being put into the first flight of the Orbiter. Then they believed we could do that.

While this is a little bit more in detail, I think Allan Thirkettle gave an impression about the various pieces that had been developed by different companies.

We had eight different flight configurations with different hardware. The point was we had to make a configuration control system without having the computers available which are available now, to control every detailed interface, every detailed item on those eight different flight configurations.

Our schedule before we came to our Critical Intermediate Design Review (CIDR) was delivery of flight unit one to NASA in about the last quarter of 1979. We delivered, finally, in 1983. We had huge problems, of course. One of the key problems was that when we started in ERNO, I had about twenty people being involved with some consultants from the United States, from TRW, and from McDonnell Douglas.

When we started the Phase C/D, I had about a hundred people, but there were also a hundred people coming from the United States. I mentioned Mr. Jack Lee's team and about eighty from the ESRO side. So we had more people from the government in the first kickoff meeting than we had of our own people. As you can imagine, we didn't have enough room at first. We had to go into a canteen. The other people working in the area didn't get lunch. So we blocked the canteen, and we had to answer hundreds of questions, but we couldn't answer hundreds of questions because we had just started to go into the detail.

The point was that from the eighty to one hundred people we had in approximately mid-1975, I had to build up a team on my own side up to six hundred people. It took me three years to do it. This was one of the problems we had, of course, and one of the reasons for a delay in the time schedules, but there were many other reasons, and I will come to those.

In 1979, NASA had a busy schedule planned, about 15 Shuttle flights planned within six months. From the beginning, one of the requirements was that we had to design the Spacelab so that within 192 hours after the landing of the Shuttle and the restart we had to exchange all the experiments out of Spacelab. We had to verify that all the other points when putting up a new payload were rightly connected and that the system was operating well. Therefore, the Spacelab was designed so that the racks were on the floor, fixed, and you could roll in and roll out all the experiments in order to start a new Spacelab mission quickly.

It never went through, of course, because NASA finally discovered that they couldn't do it. They told us rather late, so we had no chance to change the design. From the operational point of view, I guess this was a good concept finally which was still able to do things off line - not in the Spacelab. We could prepare payloads off line, and so forth.

It was about 1977 when we really knew how to build Spacelab, knew what Spacelab needed, and how to design it.

We had pallet-only missions. We couldn't fly the pressurized volume where all the subsystems were included. We had to find where to put all the subsystems that were needed to fly a pallet. All the subsystems within the Spacelab itself, within the module, were, of course, under pressure. You always had air. So, the heat dissipation and everything had to be maintained. Otherwise, we had to develop a new set of subsystem hardware. We created a can, which we called the "igloo." It had a pressurized atmosphere inside where we could use the same equipment we were using in the Spacelab module.

We used mock-ups where we looked at how the astronauts can work if they have those racks here. There were different schemes we looked upon. First of all, we had a grid on the floor so that the astronaut with a special shoe can lock in. But that was rather complicated. So we said, we will use those rails. We invented the rails in our habitation investigations. Also, together with our American friends, we developed the rack procedure, which we use now in the Space Station again. We used a 19-inch rack, which is common also in a normal laboratory on Earth.

The first review of the habitation with the European astronauts included Claude Nicollier, a Swiss astronaut, who is still flying; Wubbo Ockels, a Dutch one; myself; Ulf Merbold; and I forget the Italian man's name, but he is also still flying. This was the crew to whom we showed the whole Spacelab, the internal design, and discussed with them what to change, what to modify, and so forth. We did that also with the American astronauts. They made a formal review about the inside of the Spacelab, especially areas like the airlock. Through the airlock we put payloads from the inside to the outside directly. This was a piece which, from the safety point of view, was very difficult to design.

The first build-up of the engineering model had racks typically mounted on the floor, and you could roll that in and you could roll them out. Those scaffolds were, by the way, the contribution of Ireland. Following the principle of the geographical return, this is what the country pays in. They have to get it back through contracts and these we procured from Ireland.

On the complete engineering model we have the pallets and engineering model. We had a long debate, Allan, I believe, about how to make qualification tests on Earth with such a big beast. We didn't have such big shakers; we couldn't put it on a shaker. We could not simulate the environment, so to speak. We still had to make sure that the temperature inside in all different positions of the Spacelab in the Shuttle vis-á-vis the cold or the hot background - we had to keep certain temperatures. We could not test it. The first flight, and Allan reported about that, of Spacelab, which was a great success, was also the first qualification test of the Spacelab.

On the integration facility we had the racks, ground support equipment, and checkout equipment. We had the engineering model and the flight unit in preparation together.

There was a cartoon our guys were putting up at the time before we sent the Spacelab over to the United States with the C5A, which first landed in Bremen. Bremen has not a very long landing strip, so it was rather crucial. Also, the departure of the C5A could only be done with half the fuel; it had to be refueled in Ireland. Otherwise it could not fly. In the cartoon, we said, "NASA, we are finally coming."

We had many people on the government side, at NASA, in ESRO, international countries, but also on the teams on both sides of the Atlantic. I think they remember this program as the best program they ever did in

their life. This is because it was the first time we were doing it. I had not learned how to build a manned spacecraft at the Technical University in Berlin. Nobody told me. And this was true for everybody.

We were sometimes really at the edge of a mountain, either to fall down or to fly, not to be successful or to be successful. We had many challenges between the United States and us. We had seen that the Orbiter and the Spacelab were developed in parallel. This generated a lot of interfaces and changing interfaces. Unbelievable. We had NASA being in the chair of this interface control panel, and of course many changes were generated, and many changes were being asked for the Europeans to implement rather than by NASA.

This, of course, led to the fact that we overshot the original price dramatically, by a little bit more than forty percent, and twenty percent over is the normal limit in Europe. Beyond that, countries can leave the program. The price was not only increased due to the many changes, but there were also many internal reasons.

We had to negotiate those modifications with our subcontractors and co-contractors of which, in Europe, we had more than fifty subcontractors working on the same program. They all had to be coordinated. They all had to be on time. They had to use the same rules. They had to reuse the same parts, and so forth. Many of the parts we used were not really tested, and qualified. For instance, you had to use parts inside the module that would not poison the atmosphere. Many of those things we discovered, which we never dreamed of before.

For all of us, and for all the unmentioned people here, I would like to thank them because they all contributed to the success of the Spacelab. The first study for the Space Station was in 1983. We called this European contribution Columbus and Ernesto Valerani was one of the fathers calling it Columbus. Do you know why? Because we wanted to meet the United States in space, on a new Space Station, with a European module called Columbus 500 years after Columbus discovered America. That's the reason why our module was being called Columbus.

Thank you very much.

Axel [Roth] said that the good old days went back about 20 years. Well, I'm going to talk about the *real* good old days and go back about 30 years and carry up to the good old days. I'm going to talk about some of the agency planning that went on in the early 1970s that dealt with the design and development of both the Shuttle and the Spacelab.

The Shuttle is the primary provider of the resources that the Spacelab required which, in turn, the users required. At the same time, Spacelab, as you will see, was a major payload for the Shuttle. There were a lot of Spacelabs planned. So there were a lot of interchange of requirements, constraints and things that Klaus [Berge] alluded to earlier. I will tell you a little bit about some of the early planning.

One of the first major traffic models that came out was in 1973. This model had 725 Shuttle flights over about a 14 or 15 year time period. This model included NASA, Department of Defense (DOD), commercial flights, and foreign payloads. It primarily justified the development of the Space Transportation System (STS) to the General Accounting Office (GAO).

Some of the out-year flight rates that were assumed were 60 Shuttle flights per year, 40 of those out of the Kennedy Space Center (KSC) and 20 of them out of the Vandenberg Air Force Base on the West Coast. The launches from KSC would go to inclinations from 28-1/2 up to 57 degrees. Vandenberg would cover inclinations from 56 degrees up to 104.

Of those 725 flights of Shuttle, 276 flights included Spacelab payloads both in a dedicated mode and in a mixed cargo mode. A mixed cargo would be maybe a single pallet flying with a deployable satellite or something of that sort. Although most of the West Coast flights were DOD, there were a number of Spacelab flights planned from there.

In 1974, the Shuttle traffic model was reduced to 572 flights. This was developed to justify NASA's procurement of the STS. The out-year flights now had dropped to about 50 flights per year. We still had launches from KSC and Vandenberg. Of those 572 flights, 226 still included Spacelab payloads in both dedicated and mixed cargo modes. That amounted to anywhere from 25 to 30 flights per year of Spacelab. You will see later that this was a little optimistic.

In 1976, the traffic model came down a little bit, to 560 Shuttle flights, and these were over about a 14 or 15 year time period. It justified the five Orbiter fleet to the Office of Management and Budget (OMB) and the GAO. Out-year flights were now down to about 40 flights per year. Of those, 232 flights were still Spacelab payloads and again from both coasts of the United States.

In 1977, the model was down to 487 flights over about a 14 year time period. This model was based on budget guidelines from the Office of Management and Budget. It was used in NASA's 5-year plan in 1978. In this model 213 flights included Spacelab payloads. The hardware required to fly all those flights were four core and experiment segments of the module. That is four complete modules, plus 25 pallets, and three igloos.

In subsequent years, budgets for both the Spacelab and NASA science reduced that a little bit. The Spacelab hardware inventory finally ended up with two complete modules, ten pallets, two igloos, and two instrument pointing systems (IPS).

For these early traffic models, a number of mission scenarios were developed covering the first 20 Shuttle missions. This was to provide an envelope of the payloads that were planned for launch on the Shuttle and provide the STS development with some design parameters. It included their orbits, the size, weight, shapes, and unique requirements like power, et cetera.

In addition, six design reference missions were developed in support of Spacelab. They were a multidiscipline science mission, an Earth observing mission, a celestial solar pointing mission, a microgravity sciences mission, a life sciences mission, and what was called an AMPS, or "Atmospheric, Magnetospheric, and Plasmas in Space" mission.

These were also developed to provide an envelope of the science discipline requirements for the utilization of Spacelab. They provided orbits, the pointing for both Shuttle and the IPS systems, the weights that we would carry to orbit and return, configurations, i.e. modules, pallets, IPSs, et cetera; power and cooling that would be required on orbit, on the pad, and on landing. Some of these missions required early and late access for specimen loading or unloading. Consequently, we had cooling even on the pad during launch, and on landing, within the Spacelab.

Other requirements included data rates that would be required; the crew that would be required to support these payloads' commands uplinks; and, in some cases, launch time constraints that might be required of the Shuttle. As part of that activity, a payload planning database was developed for utilization in this planning activity. This included all the payloads that would be flying on the Shuttle and was a very large database.

In addition, requirements were developed for the payload operations control center and our ground processing facilities. Initially, there were going to be at least three Level IV type facilities: one at Goddard, one at Johnson Space Center (JSC), and one at Marshall. Later, this was consolidated at Kennedy Space Center (KSC) in either 1978 or 1979. But the requirements for those facilities came out of these early studies, and also included the data processing facility that is located at Goddard. This included real time data that had to flow through the system and also post-mission data processing.

I talked a little bit about some of the organizational elements within the agency that were for Shuttle user inputs into this planning activity for the development of the overall capabilities. Sort of the top level was a SSPPSG, which was the Space Shuttle Payload Planning Steering Group. It was chaired by Phil Culbertson in the Office of Planning and Program Integration (OPPI). This office was set up for the purpose of serving as an agency focus for the integration of requirements and planning for both Shuttle and Spacelab utilization. Culbertson served on the Level 1 Shuttle Configuration Control Board and represented the users.

Sort of the next level down was called a SPRAG, or a Shuttle Payload Requirements and Analysis Group. This was chaired by O.C. Jean at Marshall in the Payloads Project Office. It provided the detailed analysis and support to the SSPPSG. Mr. Jean served on the Level 2 Shuttle Configuration Control Board, again representing the payloads.

Another activity, more related to the user organizations, was the Joint User Requirements Group. This was co-chaired by both NASA and ESA, and it was used to coordinate Spacelab requirements and interfaces. It reported both to this overall steering group, the SSPPSG, and to what was called JSLWG. JSLWG was the Joint Spacelab Working Group and was co-chaired by NASA's Doug Lord and on ESA's side, I believe Michael Bignier was the first. It provided the program office coordination of the requirements and interface activities that went on between NASA and ESA.

In addition, there was an Integrated Payload and Mission Planning Group that was established at the Marshall Space Flight Center. This was an engineering support element, and it provided most of the analysis that went into the above organizations. It was also the one that developed and maintained the payload planning database, which was a major source of information utilized in the early design and development activities for both the Shuttle and Spacelab.

As has already been stated, there were a number of development programs that were carried out in parallel. This necessitated close coordination and continual updating of requirements and constraints to ensure the overall systems were compatible and complementary.

Some of those programs were the Shuttle; Spacelab; the ground processing facilities at KSC; the payload operations control center facilities, which started out at JSC and was later moved to Marshall; the Spacelab science instrument development activities that went on in parallel with all this; and the data processing facility at Goddard. This included not only the hardware development aspects of all this, but also the software.

Most of these development programs involved multi-field centers, NASA Headquarters, science users, ESA, and foreign users. It was an effort that will be very, very similar to what is going to happen and is happening with the Space Station. One of the earlier activities also dealt with assignment of mission management centers and the supporting science for these early Shuttle flights.

The Shuttle flew four Orbiter flight tests to verify and check out the Shuttle. On the second flight, the Office of Space and Terrestrial Applications (OSTA) payload, OSTA-1, was flown. It was an Earth-observing mission assigned to JSC. The science was selected through an Announcement of Opportunity (AO) process initiated in 1976.

The science and the mission both provided support to the early flight test objectives of the Shuttle in addition to providing science to the users. It utilized a single Spacelab engineering model pallet. This pallet, since it was an engineering model, had to be flight qualified. It flew in November of 1981.

The Orbital Flight Test (OFT)-3, which was the third flight of the Shuttle, carried the Office of Space Science's 1 payload, OSS-1. This payload was assigned to the Goddard Space Flight Center (GSFC), and it was a solar/stellar-pointing mission. Again, the science was selected through the 1976 AO process. It also utilized a single Spacelab engineering model pallet.

The planned next two Spacelab flights didn't turn out to fly in the order of next two, these were Spacelab verification flights and were designated Spacelab-1 and Spacelab-2. These flights were assigned to the Marshall Space Flight Center. The assignment included not only the mission management but served as

the focus for pulling most of the supporting activities together. It also included the management of the science instrument development activities and included the coordination of the real time science activities conducted during the mission.

Spacelab-1 was a multidiscipline science mission with both NASA and ESA participation. The science was again selected through the AO process. It flew in November of 1983.

Spacelab-2, it turns out, flew as the third major Spacelab mission after Spacelab-3. It flew in July of 1985. It was a solar/stellar mission which utilized the pallet configuration with the IPS, and the science again was selected through the AO process. These missions provided both science and verification of the two Spacelab configurations. In addition, these two missions selected and managed the payload specialist crew members who were nonprofessional astronauts; they were the first of the payload specialists that flew.

As you can see, the activities that went on in support of Spacelab and Shuttle, the early planning, is very similar to the activities that are going on with respect to the Space Station — putting together traffic models, determining science requirements, identifying supporting activities and elements, and so forth.

That carries me up to the good days.

What I thought I would do is just to delve into a few of what you call the war stories, because what really put this program together was the people. We had all sorts of systems. Bob [Benson] has just told you about some of the boards that I mentioned in the presentation that I gave earlier. Happily, the people that really put the program together were, to some extent, decoupled from all of that stuff. It was the people that put the thing together, and it was the people that did the learning, and it was the people that had the pain. But, it was the people that had the fun as well.

We, collectively, were terribly naive when we started this program. Klaus [Berge] mentioned having only 20 or 30 people as a prime contractor early in the program and, even at the kickoff meeting, having about 80, and yet having 200 civil servants come to visit with him. The naivete was not just on the technical side. The naivete was also in that ERNO canteen, because the food was abominable. Those people that didn't get lunch — you really did them a favor!

To be more serious, we had a situation where Spacelab was not an autonomous laboratory. It had to get its resources from the Shuttle — power, data, that kind of stuff. Therefore, of course, the Shuttle would switch on Spacelab. So we get this nice design and assumed that the Shuttle was off there with its little switch that would do it.

Of course, it doesn't quite work like that because you have to have a sequence of activation. Certain things have to be on before other things. Otherwise, it doesn't work. Yes, the Shuttle had got its switch, but it assumed that Spacelab would take care of all of the sequencing.

I think it was about 15 or 18 months into the program where all of a sudden we realized that we needed a thing called a remote activation and acquisition box, or RAAB. The internal layout allowance of the vehicle was already in place and we had no space for this box, which was the size of an orange crate. To this day, as far as I know, this box is still there on the floor just underneath the hatch of Spacelab. That box was probably one of the most complex boxes that we had to put on the vehicle. When we started, we had no idea we needed such a thing.

We also knew, of course, that electronics had to be cooled. There was a fairly sophisticated air cooling system, but there was also a necessity to have an active fluid cooling system.

The in-thing right at the beginning was normal refrigerants. Then, as Klaus mentioned, you run the risk of poisoning people if you use certain fluids. Some nasty person told us we weren't allowed to use freon. So we had to develop a water loop, very, very sophisticated cold plates, extremely light. These things had to absorb heat from boxes.

Well, you all know what cold plates are. But in order to absorb the heat properly from cold plates, all the clever analysis people told us that you've got to have perfect contact, perfect surface-to-surface contact. You can't get perfect surface-to-surface contact. You try and screw the cold plates tightly onto the boxes and the cold plates collapse because they are very, very thin.

So we had to invent a thing called a “thermal filler,” some quasi-liquid stuff that would enable the cold plates to be attached to the boxes and which worked perfectly thermally. Unfortunately, this “goo” kept pouring out between the box and the cold plate. That also was a typical piece of naivete. We realize that surface-to-surface contact is what you read about in textbooks. In the real world, you get things like conduction that work perfectly okay.

We had a fun time once. We were trying to make sure that the Spacelab would always fit physically inside the Orbiter. We were held on by trunnions. The Orbiter, when its payload bay doors are open, is an extremely flexible beast. Under thermal conditions it will breathe quite significantly.

Spacelab on the ground, of course, has got one atmosphere inside it and one atmosphere outside it. When it went on orbit, happily it still had one atmosphere inside it, but a vacuum outside. So the shape of the Spacelab changed as a result of being on orbit. You could build things to drawings, but there are nasty things like manufacturing tolerances and inaccuracies of the build that come into play.

We had about 1 to 2 inches to spare between the nominal “as drawn” position of Spacelab and Orbiter and what might happen under extreme cold and extreme hot circumstances, and what would happen with manufacturing tolerances of the Shuttle and the Orbiter.

We didn’t have Cray computers in those days. We were about one stage beyond the abacus, I think. We certainly didn’t have big computers to help look at the some 250 different thermal and mechanical design cases that we had to check for relative deflection to make sure that Spacelab didn’t hit the Orbiter, or worse yet, didn’t fall out of the thing.

There were a couple loads analyses done by Rockwell, a couple of thermal analyses were done, a manufacturing tolerance assessment were performed, and we had a great big meeting in Bremen. There were 25 people sitting around the table, mixtures of Rockwell, NASA, ERNO, and agency people. Each of them had a particular task. One had to worry about what load case it was; one had to worry about the mechanical deflection; the next, the thermal deflection; the next, the manufacturing tolerances.

We had all agreed that we were going to root-sum-square all of these things. But, of course, all the Rockwell data came in inches — damn them — and all of the European data was in millimeters. So one guy was appointed the official task force “metrificator” and we literally passed pages of paper for every single load case from one person to another. There was a guy at the end who had to work out which was the worst case plus, which was the worst case minus, and, to this day, that was how the length of the Spacelab trunnions was determined. The people that worked around the table got to know one another very, very well indeed. Most of us are still in touch with one another, and there are still 2.54 centimeters in an inch.

Getting back to naivete again. We wanted to save a lot of mass in the early days on Spacelab. The pallets were one of the things that were being attacked. So it was decided that a lot of mass could be saved by building from this terrific new stuff called carbon fiber. Oh, this was wonderful. We were going to build all of the panels from carbon fiber. I can’t remember the numbers, but my stomach tells me it was something like 200 kilograms of pallet that we were going to save, which is huge considering the total mass.

We went through this exercise. Industry developed some test pieces of carbon fiber honeycomb, and these things were fine; they were robust; they were strong enough. Everything was great. And then some miserable individual pointed out that this thing was going into space. It was going to be great at room temperature, but if you were at plus 100 or minus 100 degrees centigrade, carbon fiber wouldn't expand or contract and the aluminum would grow and contract like hell, and all of a sudden all the bolts failed.

We took out 200 kilograms per pallet to go to carbon fiber. We had to put in 250 kilograms to go back to aluminum, because industry always wants their pound of flex**,** of course. That was another typical piece of naivete, a wonderful little design cycle that we went through.

One last little story that I wanted to mention. Klaus talked about the inability to perform shaker tests and overall thermal balance tests and that kind of thing. Yes, we qualified and were accepted on the basis of analysis, but there was good news and bad news on this thing.

The bad news was that, on the mechanical side, we went through the cycle of coupled loads analyses that now are old hat in the Shuttle world. Every payload of significance that goes inside the Shuttle goes through a routine of coupled-load analysis cycles, and they have an uncertainty margin in each of those stages of the cycle. You reduce the uncertainty margin as you get more and more mature in your design, and, generally, what you design for initially is pretty well confirmed at the time of the verification analysis.

On Spacelab, we went through the cycle. The cycle was being invented. It was not a standard cycle at that time. What we didn't do was go through the margins and the uncertainty allowances. After we had built and integrated the flight unit Spacelab in Bremen, the famous 5.7 / 5.8 coupled-load analysis was done by Rockwell, and that analysis pointed out that we weren't designed for the right load factors. We had to pull that wretched flight unit apart for eight months and reinforce it.

Subsequently, we found out through flight test experience on all the missions that are flown that those loads were never experienced at all — nowhere near. We wasted our time, and our money, and some mass to put all of those modifications in. But, because we were doing things by analysis and there was that uncertainty, we got some bad news.

The good news relates to the logo that I showed on the first slide (Figure 2, page 18) — that wonderful multicolored, multi-flagged Spacelab logo on the forward end cone of Spacelab. It cost a lot of money, that thing. In 1973 prices, it was 90,000 accounting units. Silk screen printing, and all sorts of outgassing tests to make sure the colors would stay fast and everything else. It was our pride and joy. We were so happy for that thing to be on there. When the Spacelab was finally first put in the Orbiter and the astronauts or anybody could look out of the aft flight deck, there were these two huge logos shining.

It was a fun program. I just wanted to share a few of those points with you. Thank you.

I'm going to give you a little bit of insight on what it was like to use the hardware that these guys are talking about and how to put it together to do science, which is what the program was all about.

Unfortunately, we were going to try to do all the science that NASA ever wanted to do on one flight. That caused a great deal of difficulty. Allan [Thirkettle] pointed out that the international agreement said up front that it was going to be a joint mission and roughly shared 50/50. Our biggest problem was, how do you divide everything 50/50?

In the strict sense of two sides of the ocean trying to negotiate, we divided everything in half. It was half the weight, half the power, half the crew, half the daytime, half the night. We divided everything.

Then we all sat down one day and said, "This doesn't make any sense at all." We started doing a little bit of give and take. Some of us learned our first German, which is "ein grosse bier." We had to learn that to get through the process.

The process actually worked pretty well. It was a fantastic learning experience for me, and I know for people at Marshall [Marshall Space Flight Center (MSFC)] who had an opportunity to participate in it.

The charts are just background to keep you familiar with what the first flight really looked like (Figure 1). On both sides, we created organizations that pretty much mirrored each other. At Marshall, I was mission

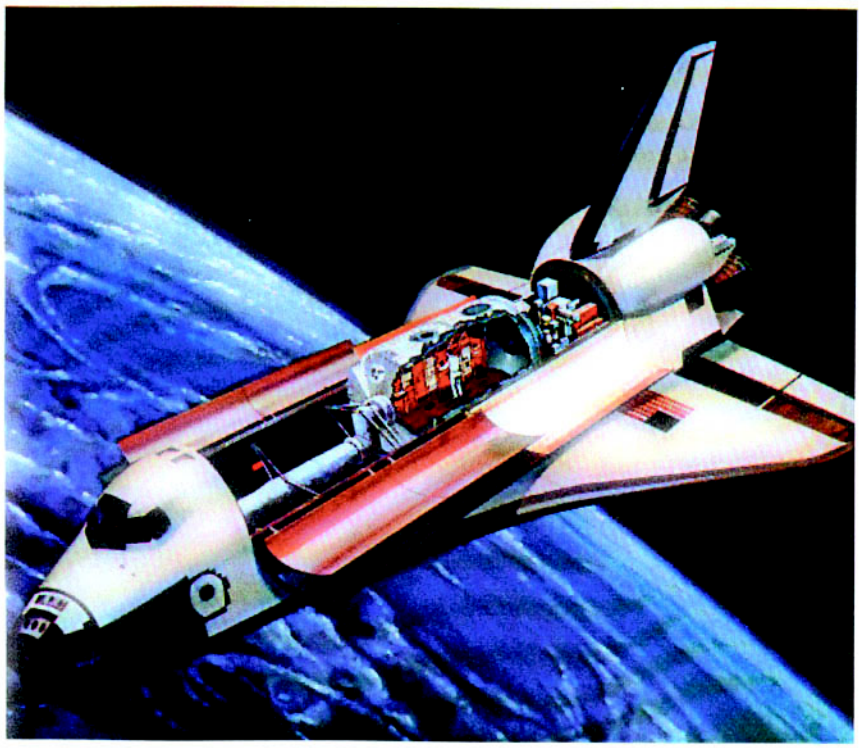


Figure 1. Artist's concept of Spacelab in the Shuttle.

manager. In Europe, they had an organization called the Spacelab Payload Integration Center in Europe (SPICE). I honestly had forgotten what it stood for until Allan mentioned it. Although, I did remember the acronym. Derek Mullinger was sort of my counterpart on that side. We pretty much mirrored each other and worked the processes together.

If we were doing it again today, one thing I hope we would have learned is that we probably should have created it and treated it as one payload. But, for a long time, we treated it as two payloads, an ESA payload and a NASA payload. By the time we flew, we treated it as one. I think today we would probably learn that lesson a lot sooner, and on the subsequent Spacelab flights we did. We did utilize what we learned, and it was really just one science payload. We let the science community get in and take more charge of how we divided the resources and what we ought to do.

Allan pointed out there were about seventy experiments on board. We used to have fun counting them. ESA wanted to count it up into the hundreds or two hundreds and NASA wanted to count it to the lower numbers.

On the first flight, we had microgravity; we had life sciences, which is really microgravity; we had the space plasma physics investigators who wanted to look at the atmosphere around the Earth; we had the astronomy investigators who wanted to look at deep space; and we had the solar investigators who wanted to look at the sun. We had to do all that in a seven to eight day mission. That really got to be fun.

What happened was the science community began really levying and putting requirements on itself. For the solar investigators, when you point at the sun, everything on the pallet was going to get nice and warm; when you looked at deep space, everything was going to get cold. And the requirements kept growing. We actually did each other in, in terms of some of the design extremes. Again, it was a verification flight trying to prove that the hardware was going to work, not so much the science.

We had a lot of issues on the standards. I watched [the International Space] Station (ISS) being developed before I left NASA, and I think they've got their approach to where they won't have as big of a problem. We had a lot of problems between the NASA and European standards. I just loosely use the European standards because a lot of the countries involved had different standards.

Somebody mentioned that the electromagnetic interference (EMI) worked real well, but we thought it was going to be a big bear. It got worked real hard, which is why we didn't have the problem. We ran EMI tests one after the other.

We also found out very early that we were going to have to manage what we call " critical resources". We found out very early that a lot of things weren't critical, but there were things that were. Power turned out to be a very critical resource — weight was too, as you might expect. Also, the crew time turned out to be a critical resource.

A number of the other things didn't really bother us. The thermal design and things like that you can say are tied some way to power, and that is true. But, in general, those were the three things we worried about most.

One of our biggest problems from a science standpoint was that the science was being developed in parallel with Spacelab, and Spacelab was being developed in parallel with the Orbiter. That created a lot of problems. We never really knew when we were finished, i.e., the coupled loads kind of thing. We just never knew when we were finished.

The safety process took a lot more time than we thought. A lot of us that had really grown in manned space flight still had a lot to learn about what it was going to take to put a complicated Orbiter-Spacelab together and prove to everybody that, in fact, it was safe. We did a good job on that, and the process has improved. On Station, I hope they can take advantage of everything that we learned.

From an operations standpoint, the time line was far more difficult to build than we ever thought. When we actually got on orbit, some of the stellar targets and some of the opportunities to look at the sun and some of the opportunities to do microgravity effects on the crewmen and/or to grow crystals or operate an oven, all started just jumping on top of each other. We ran the time line and we re-ran it. Then, when we got on orbit, we ran another one.

The only thing I can say to you is that we did a lot of planning on the ground and then we implemented a totally different time line when we got on orbit. In retrospect, we probably should have understood that that was going to happen.

I guess one of the things that I thought was unique about the flight was that we finally took scientists into orbit (Figure 2). I think that was a fantastic achievement. I hope that within the agencies both in Europe and in this country — and our friends in Japan as well — that we can continue to fly the scientists. I think that was a step forward, and I still believe that very strongly. Those crewmen performed just as well as any other crewmen that we have ever flown.

We also did the first step in diversified training. We actually didn't do every bit of training at one location. We sent them around all over Europe, Japan, and the U.S. That worked a lot better than anyone gave us credit that it would. We also had to do what I call some integrated training back in Huntsville [Alabama], and SPICE did some integrated training in the Cologne area.

The payload control center worked well. When we got started, I really believe there were a lot of people on the Space Transportation System (STS) side that wondered if a group of scientists and science-related people could actually take control of a complex mission and pull it off. Gene Krantz, whom many of you know, gave us one of the biggest compliments. He came up after the mission and told me, "I expected any day to have to pick you guys up off the floor. You did a fantastic job, and you're a tribute to the agency." Gene didn't pass out compliments lightly. So we took that one to heart.

We spent a lot of time on software. I'm afraid that from now on we will spend time on software. I don't see that kind of thing going away. Just make sure that as we go into Station we have adequate capability to modify, build and add to, because that will happen.



Figure 2. Inside the Spacelab module.

I would like to talk about KSC operations from a payload standpoint (Figure 3). You heard a lot about it and you saw a lot of pictures. The only thing I can say there is that there were a lot of long days and nights.

We were constantly redoing. We put racks together, and then they would change something in Bremen. We got them to the Cape [Canaveral], and we got another set of load factors. We had to go in and de-integrate racks and stiffen the posts. I agree with my counterpart here. We probably never really needed to do that, but the piece of paper in front of us said we should, and we did. I don't know how many times we put the thing together and took it apart. It would be interesting if anybody really remembered how many times we took some of that stuff apart and put it back together.

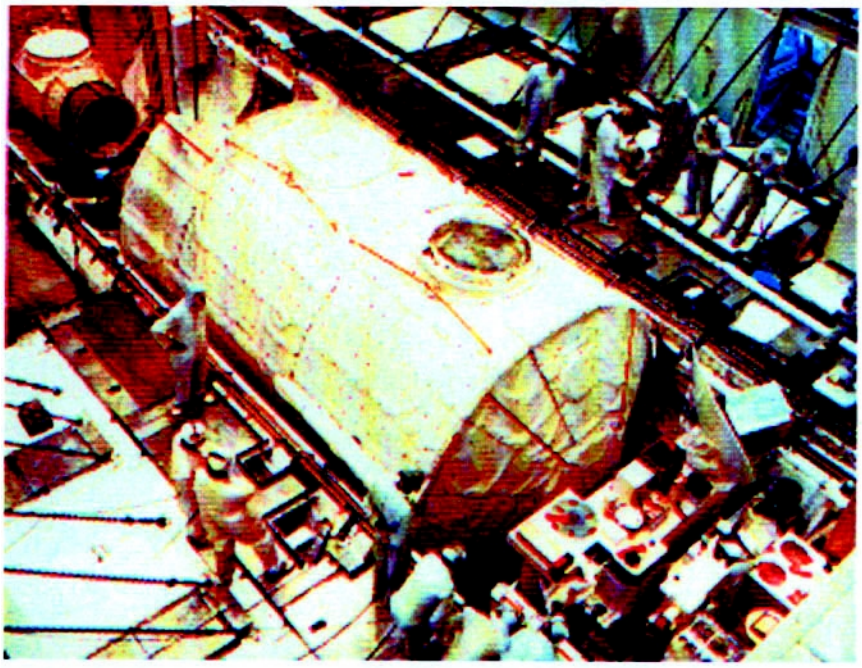


Figure 3. Integration at Kennedy Space Center.

I will endorse something Allan said earlier about the mission sequence test. I became a fan of that, and for the many Spacelabs after the first one that I was associated with, that was a real key test at the Cape. It always gave us a lot of assurance that the thing was going to work properly.

For the results of the mission, as complicated as it was and considering the many ways that we looked at it, we actually got good science from every experiment on board (Figure 4). Some of them worked longer than others. That was by design in some cases; it was not by design in other cases; but virtually every experiment came home with some data to analyze (Figure 5).

There were numerous papers presented. I'm not sure what the total might be, but I know there were numerous papers written by the science community as a result of the data from the flight.

What is it going to look like when we go to Space Station? I've been out of touch with the agency maybe for a year now. So, if I say something and everybody knows that it's different, please bear with me.

From a Spacelab standpoint, we drew heavily on Skylab. Some of us asked the Skylab people, how did you do this? How did you do that? Why did you did this? Why did you do that? We learned a great deal from them. I hope and pray that Space Station, both from a design and operations standpoint and a flexibility standpoint, learns a great deal from Spacelab because it was a great piece of hardware and it had a great deal of flexibility.

Some of the things that I think we did right. I think we did right with the high degree of science involvement. I'm not sure all the scientists loved me when the mission started, but when it was over we were still friends, thank goodness. The science crew, I think, was a positive aspect that I hope we don't lose.



Figure 4. Launch of Spacelab-1.

I believe, as every one of the speakers has said, we paved the way for strong international programs. We learned how to work with one another, we learned how to trust one another, and we learned that there is not only a U.S. way to do it or a NASA way to do it; there are multiple ways of doing it. That was good for both of us.

The distributed operations have proven that it works well. I think now that we have the Internet capability there is really absolutely no reason that scientists can't stay in their laboratories and work and control an experiment on board the Station.

One last parting thought: safety is of paramount concern to all of us. Nobody wants anybody to take a chance there. The safety process — we've just got to make sure that we do that in a straightforward reasonable way. We must learn as we do it and get more comfortable in implementing it.

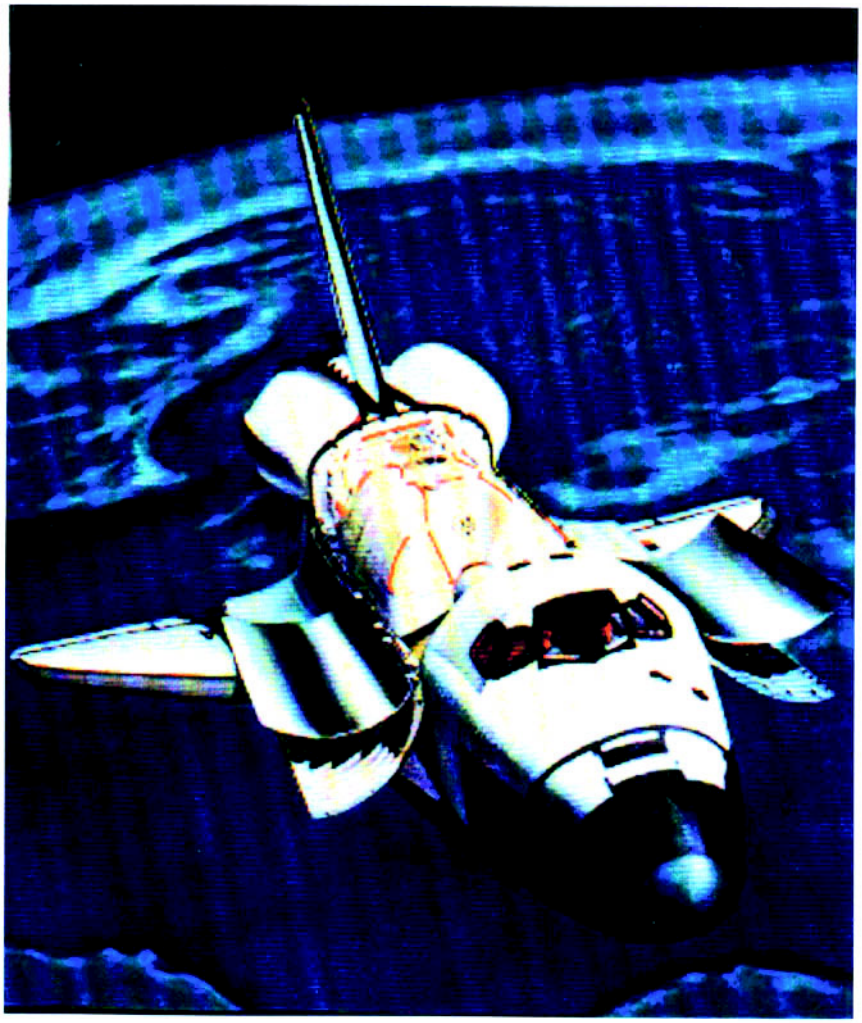


Figure 5. Artist's concept of Spacelab in the Shuttle Cargo Bay.

Mr. Roth: I want to reiterate what Harry [Craft] just talked about, that is, what we learned on Spacelab and, prior to that, on Skylab. Getting back in the Space Station program in January for, I think, my third and hopefully, the final time, I do know that they have taken the lessons learned in Spacelab to heart. At least most of them that we can, even to the testing down at KSC that is coming back into the program more so than what it was before.

Now I would like to open it up if anybody has any questions for any of the panel members.

QUESTION: I do research in gene therapy which involves a number of complex procedures, such as isolation of stem cells, gene transfer, bone marrow transplantation, and gene expression. If we use mice or monkeys, we have to see how these animals can be cured. With all these complex procedures, I wonder, how we can do it? If we have to depend on payload specialists and control from the ground, this kind of complex experiment may be rather difficult. How do you envision to solve this kind of problem?

MR. ROTH: I might let Harry talk to it a little bit more, but I think he alluded to it. I think he made an important point in that we have to have payload specialists, or what the agency has called payload specialists. In other words, experts in that field need to be able to go to Space Station. I don't think there is any other way to do that, quite frankly, especially in those specialized areas.

MR. CRAFT: The only comment I would make is that I think that we have got to continue to involve the science community strongly. I don't know that I appreciated that; I don't know that I would have said that in 1976 or whenever we started Spacelab. I only said that later when I recognized that the scientists honestly communicate in a different way than the engineers do.

When someone with the knowledge and capabilities related to your discipline can act on your behalf, I think you will build some mutual trust with that individual that allows them to maybe make a modification to an experiment as it is being run or change something based on their knowledge and your confidence in them.

Space Station ought to allow you a great deal more flexibility. With the communication systems and the software that we have, you ought to be able to stay right on top of the experiment.

The degree of trust we had with the crew and their science counterparts on Spacelab-1 was fantastic. The degree of confidence that you have in that individual may be fantastic in the future, but you're going to have so much more insight into what they are doing just because the communications capabilities are there. It ought to make life a lot easier and let you do a lot more complex things with the same degree of easiness.

QUESTION: Harry placed great emphasis on the scientific community's involvement during the Spacelab operation period. I can see there is maybe a difference during the buildup of Spacelab versus building up of Space Station. During the Spacelab period, maybe you did not have a huge scientific community out there, though you still had to engage them, to tell them the Spacelab capability would be available so many years down the stream.

Right now, we do have a big scientific community out there and there is a huge competition — for instance, on the resources, on the budget, on everything. How do we continue to engage the science community during this buildup period which could be three, four, or five years? What advice do you have from lessons learned? It's a little bit different environment. Right now we do have an established space science community versus the one we may not have had.

MR. CRAFT: I'm not sure I can address that one because I'm not that close to Station.

MR. BERGE: I can say something for Europe. In Europe we have various panels, in particular in ESA, the European Space Agency. They prepare AOs. The type of the AOs is not safety or anything else; it's the science. We want to have the best science. So, it's a competition on the best science because you cannot fly at the same as time all those scientific instruments. We will have periods staggered. There will be half-year periods in which a change of experiments takes place and new experiments come in. The key point is having the best science, not resources. Resources are the second or third priority to look at after the process, not in the process.

MR. CRAFT: I'll give you one final comment, and I probably overstated my knowledge. The degree of science involvement I personally think ought to grow.

Maybe you are doing better at this now than I would give you credit for. If you go back and look at Spacelab-1 and then if you look at the Spacelab flights after that, I think we started heading in the right direction. On Spacelab-1, the science community was comprised of groups of individuals. Toward the end, they became a team.

As I saw other Spacelabs go together when I was head of payload projects, I began to see the science community cooperating more. We don't always have to have a Dornier furnace and an American equivalent of that. Somehow we have got to get to where we can have one. On a lot of the early Spacelab flights we had two and three of things because various countries and science communities wanted to push their approach to that science. Which is fine, but we could have had more science and broader science had the community cooperated.

The only advice I can give you is stick together as a community and use your opportunity as a community to come up with something that you want to push and push it as a community. You are much stronger that way. We listened much stronger when you were that way.

QUESTION: Both Mr. Thirkettle and Mr. Craft talked about safety, but I didn't get any real details. It was very important and you were evolving. Could you give a little more detail on that area?

MR. THIRKETTLE: The problem is where to start with the answer. There are some fairly obvious aspects of safety that people coming out of the aircraft world would immediately be able to take into account, like making sure that the structure is going to be strong enough, that it can withstand all the environments.

The areas that keep the man comfortable, as well as alive, have a part to play in the safety as well, although safety strictly is keeping him alive rather than keeping him comfortable. All of the atmospheric control stuff had to be in place so that the guy would be breathing air and not breathing something else.

Material selections had to be taken very, very carefully to make sure that the materials would not generate toxic compounds going into the atmosphere. In a closed loop environment, which is the nature of a manned spacecraft, that is far more important than on the ground. On the ground, you can open a window and let some of this stuff go out. If you open the window on Spacelab, stuff goes out, you included.

We had to achieve all of these things which, from an engineering point of view, are relatively straightforward to understand once you find out about them all. From our point of view, we had to learn about some of these things, but then it's the assurance of the process. It's how you go about proving; the paper-train that you have to go through to prove to not only him — but to him and him, and that so-and-so as well — that all aspects are okay.

There is a degree of subjectivity about this as well. It's not so absolute. That was another thing we had to learn, not only how to engineer it properly, but how to tell the story as well.

There was a lot of independence and there still is a lot of independence in the world of safety. Quite rightly, in those days they stayed out of the mainline design so that they could take an independent look and not be biased by the compromises that, as engineers, you inevitably made in the design process.

I personally never liked that idea very much. I thought that every engineer should have a direct responsibility for safety rather than making it the ultimate responsibility of a policeman somewhere. That's the way we worked aircraft, and I think more and more that is the way the Space Station side of the thing is working as well. There is a degree of independence, but far more a degree of interdependence. As a result of that, I think the safety panels that are running the Station have got far more ability themselves to be pragmatic and to give added value to the design process.

For us, it was more of a disciplined learning. We learned things that we would never have thought about by ourselves. The experience that came from Skylab had to be given to us; the experiences that came from the disasters at the Cape had to be given to us, and we had to learn them. It was a heavy overhead.

For those people that weren't necessarily involved in the development, certainly in Europe, there was a body of opinion that thought that this wasn't safety, it was paranoia. That was very wrong. That was very wrong. Because, in the end, there are human beings flying on these spacecraft, and those guys had better come back down alive and well.

Earth Observations
Dr. Jack Kaye

I'm calling this "Spacelab Missions for Earth Science." What I am going to try to do is just pick on a couple of the missions where we used Spacelab hardware to do Earth science.

You can look at the list that was passed out for all the missions, and you will see a number of Earth-observing missions there. But I'm going to really focus on just a few of these. This focus really just comes from the fact that I'd rather say more about fewer things than to try to say a little bit about everything that is involved. So I will be picking on two of them.

What I was going to do is first say a little bit about how space measurements fit into Earth science and then I'll be talking about the Atmospheric Laboratory for Applications and Science (ATLAS) series of missions and the Lidar in-Space Technology Experiment (LITE) mission, the ATLAS being a series of three Shuttle missions that were very much Spacelab missions.

I want to say a little bit about the history, what the missions were, and some of the instruments that we had on them, and give results. I will give the results mainly from three of the instruments. You will see a lot of acronyms and abbreviations. I will try to explain them as I go along.

Then, I will say something about the LITE mission. There was one mission in 1994 that was actually a technology demonstration mission, but some absolutely marvelous and gorgeous Earth science came out of it.

Obviously, for the Office of Earth Science at NASA, the use of space to study the Earth is fundamental and central to what we do. Space gives us the opportunity to get a global view of the Earth and to make observations over all kinds of territories, land, water, ice, developed countries, developing countries, in a way that you really can't do without that unique global perspective.

Most of what we do in space for Earth science uses polar sun-synchronous Orbiters — not all of it, but probably most of it. That provides a unique vantage point, especially in terms of global coverage.

If we are interested in the processes at high latitudes for things like polar icecaps or the Antarctic ozone hole, having something that can see to those high latitudes becomes critical. We tend to get reasonably high altitude orbits, 700 to 900 kilometers. So that means that we can get very stable long-term orbits, and some of the spacecraft that we've had have been able to give data for 15 years. There are a number of spacecraft that have made it into the teenage years.

Another thing is that by going to polar sun-synchronous orbits, we tend to remove complications from diurnal variation. The disadvantage of that is that we may be looking at two times of the day, typically once

in the morning and once at night. For a number of things it's helpful to pick specific local times because you do have a diurnal cycle in clouds and radiation, and if you have that observation time change over the course of time, that means you are sort of entangling seasonal variations, daily variations, and monthly variations. The polar sun-synchronous orbits at least get you out of dealing with the daily variation.

Inclined orbits, the Shuttle being one of the primary ways we get to inclined orbits, complement the free flyers quite nicely. If one is interested in the tropics or mid-latitudes, the standard inclined orbits between 28 and 57 degrees work wonderfully in terms of really providing most the coverage where we want it for those particular science questions.

The included orbits do provide an opportunity to view the Earth at a variety of local times. This can be helpful, especially if over a period of time we want to characterise the diurnal variation in some parameter.

Another point I would like to make is that the short-duration missions, such as we were able to carry out from the Shuttle and using the Spacelab hardware, do provide an opportunity to do some things that it is just unrealistic to expect that we could do from free-flying satellites. One is that it did give us the opportunity to fly some complex instruments that we really could not put on the free flyer with any sort of reasonable technology, cost and schedule, but with the resources of the Shuttle and the Spacelab system we could do some really neat things.

Another important point is that, with Shuttle missions, we have the opportunity to bring the instrument back to the laboratory so that we could do some very intense focusing on calibration. If you calibrate the instrument in the lab, take it to space, do whatever you do with it, and then you bring it back and take it back to the laboratory and calibrate it again, that lets you really look at these detailed calibration issues very critically.

This calibrate-fly-calibrate approach wasn't just an approach to fundamental metrology, but was designed to help provide calibration information for instruments on free-flying spacecraft that do degrade over the course of their time in space. By being able to calibrate, fly, recalibrate, and then compare, that means that it provides one of the best ways of testing what any degradation would have been for a space-based instrument.

Let me move on to the ATLAS missions. I was the ATLAS program scientist for a number of years. It was one of the intensely pleasurable experiences of my life, I've got to say.

The history goes back probably about 20 years to the original Announcement of Opportunity release for Spacelab instruments (Figure 1). There was going to be a series of missions called EOM, or Earth Observing Missions. That was going to be ten flights over an 11-year solar cycle. The solar cycle provides a lot of modulation to the chemistry and energetics of the atmosphere. The higher you go up in the atmosphere, the more significant that modulation becomes.

We had the Spacelab-1 flight that a number of the instruments that flew as part of ATLAS first flew on. In fact, after that NASA committed to refly some of the atmospheric and space science instruments from Spacelab-1 on the first EOM mission. Once the EOM missions were scheduled, then came the various

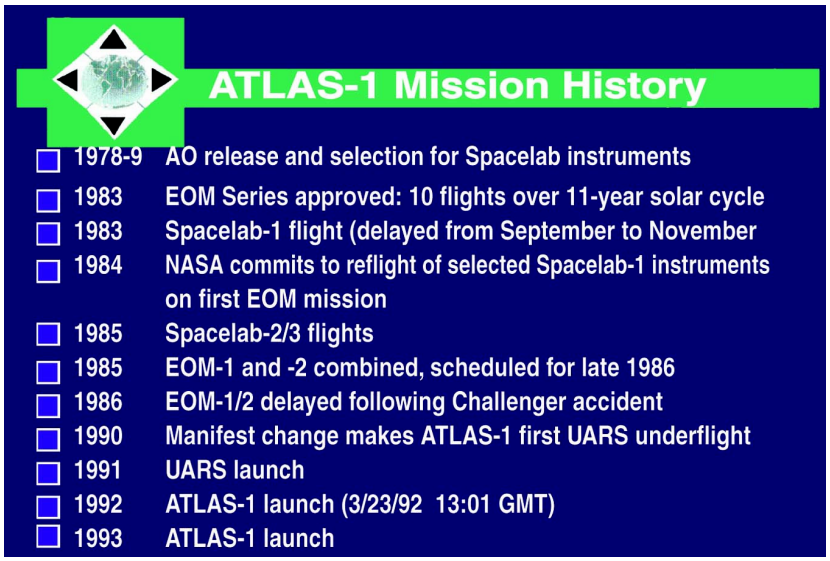


Figure 1. ATLAS-1 mission history.

manifests, with their puts and takes. The first EOMs were combined. Then they were delayed as a result of the stand-down following the Challenger accident.

Come 1990, it became clear that the first ATLAS mission (which was the new name for the EOM series) would not take place until after the launch of the UARS, or Upper Atmosphere Research Satellite, which was to come in the latter part of 1991. The history of the ATLAS program really is inextricably linked to the UARS program. UARS was, and still is, a major satellite program designed to study the chemistry, energetics, and dynamics of the Earth's atmosphere as well as the forcing of the atmosphere through solar radiation and particle input.

Besides using the ATLAS payload to do its own scientific measurements, we would use the ATLAS missions both to help validate and calibrate the UARS mission through the calibration emphasis that I talked about earlier. Over the longer term, the ATLAS missions were to help provide data sets for long-term studies of the atmosphere and its forces, as the decadal time scale for the ATLAS missions well exceeded the planned lifetime of UARS.

We ended up planning the first ATLAS launch for March 23, 1992; the ATLAS-2 launch was going to be in the spring of 1993. I am showing some charts that were prepared before launch, which ended up being delayed a day, so March 23rd turned into March 24th.

The basic structure of the mission was that we had two Spacelab pallets and few additional payloads (e.g. Get-Away-Special [GAS] cans) (Figure 2) . It was going to be an 8-day mission, and 57-degree inclination. Fifty-seven degrees is a fine orbit, as I indicated, for looking at quite a few things. The orbital altitude was nominally 160 nautical miles, or 300 kilometers.

One of the important things to recognize is that the ATLAS missions used a number of different attitudes. The way that this mission was set up most of the instruments didn't have a lot of pointing capability. The Shuttle did the pointing. So, one could be doing atmospheric science, or could be doing space science, or

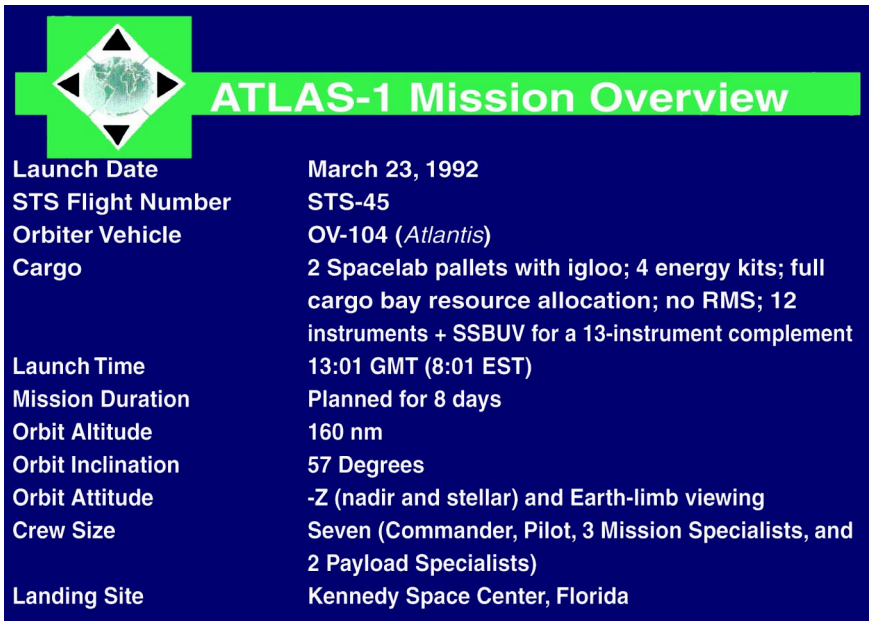


Figure 2. ATLAS-1 mission overview.

solar science, or stellar science, but not all at the same time. That gets at some of the trade-offs that Harry [Craft] was talking about earlier this morning.

This chart tries to summarize some of the history of the instruments that flew as part of the ATLAS series. I will talk through some of the acronyms.

There are a couple of things that come clear from this chart (Figure 3). Every instrument that flew on the ATLAS mission, with the exception of one, the Millimeter Wave Atmospheric Sounder (MAS), had flown

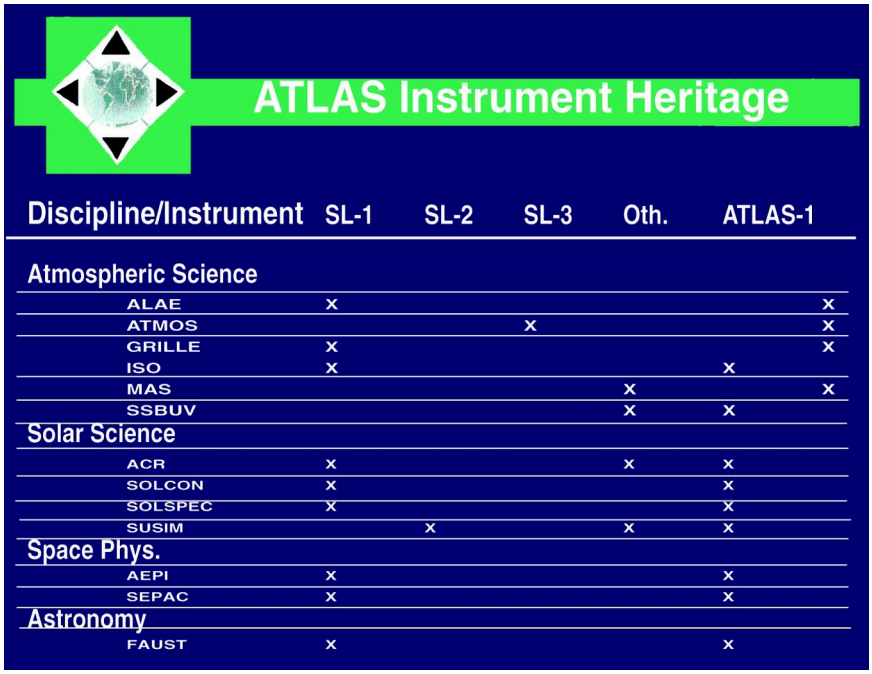


Figure 3. ATLAS instrument heritage.

before in some form or another, most of them on Spacelab-1 but some from Spacelab-2 and 3 and other places. ATLAS-1 really combined the first of what was going to be the EOM series and reflights of selected Spacelab-1 instruments. So when one looks ahead to ATLAS-2, one sees it going down from 13 instruments to seven.

The other thing that is clear on that chart is that there were four scientific disciplines represented in the first ATLAS mission: atmospheric science and solar science, which really come under the scope of the Office of Earth Science; and then, space physics and astronomy that come under the scope of what is now the Office of Space Science at NASA Headquarters.

This is a schematic diagram showing how things looked on the pallet, sort of the standard alphabet soup of things (Figure 4). There are the two pallets. Some of the instruments were very small; some of them were very big. There is a range of scientific disciplines that they were applied to.

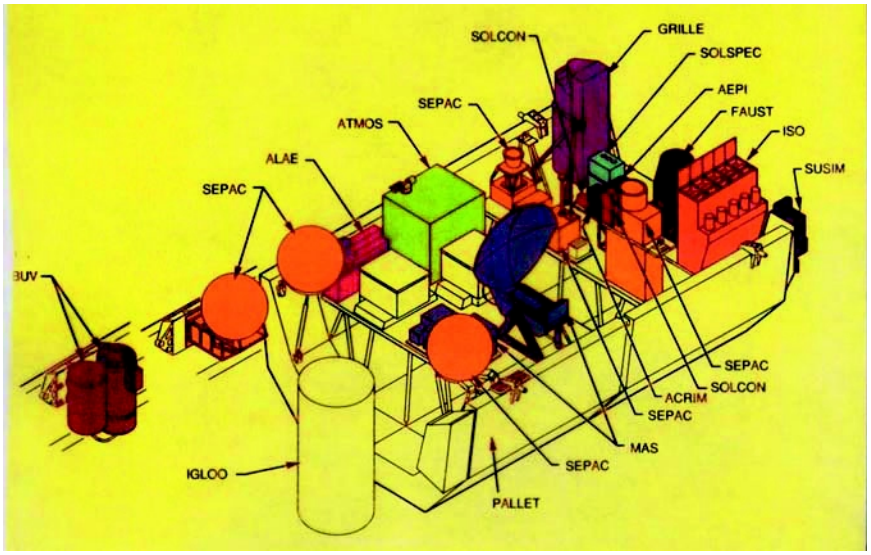


Figure 4. ATLAS pallet configuration.

There was an investigator working group that would help coordinate these things and help make the trades and establish the time line that was used to balance all the resources. The group would to try to make sure that everybody came out with what they needed to do the science that they wanted to do.

This chart just gives a sense of the science associated with the first ATLAS mission (Figure 5). The boxes indicate the way solar input and particle input into the atmosphere affects the stratosphere, which is over more towards the right, higher in the atmosphere, which is near the middle and towards the left. The colored boxes indicate which of those aspects of that basic problem were addressed with the first ATLAS mission.

You can see how the pieces link together, that if you affect, especially, the nitrogen-oxygen chemistry in the upper atmosphere and the mesosphere and thermosphere, sometimes that comes down into the stratosphere and can affect ozone. Solar radiation at ultraviolet and visible wavelengths affects stratospheric chemistry directly, and chemistry radiation and dynamics are all linked together.

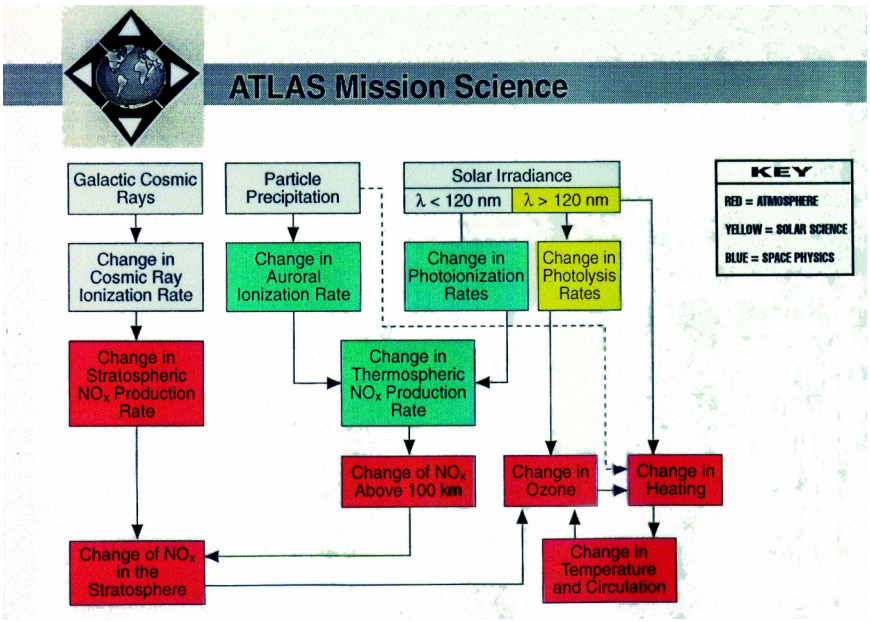


Figure 5. ATLAS mission science.

The science associated with the atmospheric and solar part of the mission made for a nice package, because it meant that we could look at forcing and response at the same time.

I wanted to say some things about the instruments that formed what were the core ATLAS payloads, the ones that flew on ATLAS-1, 2 and 3. There are three in atmospheric science (Figure 6).

One was the ATLAS instrument from the Jet Propulsion Laboratory (JPL). It was a very high-resolution Fourier Transform Spectrometer that measures more species than any other instrument that has flown in space to date, to my knowledge.

Summary of ATLAS 1 Investigations

Atmospheric Science

Investigation	Approach	Measurements	PI and Institution
Atmospheric Trace Molecule Spectroscopy (ATMOS)	Infrared interferometer	Absorption profile of molecular species in the stratosphere and mesosphere	M.R. Gunson, Jet Propulsion Laboratory,
Millimeter-wave Atmospheric Sounder (MAS)	Millimeter wave spectroscopy	Limb profiles of temperature pressure, and selected molecules in the stratosphere and mesosphere	G. Hartmann, Max-Planck Institute for Aeronomy, Germany
Shuttle Solar Backscatter Ultraviolet Spectrometer (SSBUV)	UV spectro-photometer	Calibrated ozone profiles and solar UV from 180 to 450 nm	E. Hilsenrath, Goddard Space Flight Center, United States

Figure 6. ATLAS-1 atmospheric sciences payloads.

We had the MAS, which used basically microwave wavelengths to look at distributions of ozone, water vapor, temperature, and chlorine monoxide in the stratosphere.

Then we had one instrument that wasn't actually part of the Spacelab pallet, but was treated as part of the ATLAS mission. It flew basically in GAS cans on the side of the payload bay, called the Shuttle Solar Backscatter Ultraviolet Spectrometer (SSBUV). It had a number of measurement objectives that were similar to the solar instruments that were flying as part of the ATLAS payload, but it also made atmospheric observations, mainly of ozone.

One of the nice things about Spacelab is that Spacelab gave us enough room in the payload bay to be able to do other things alongside the primary payload that were complementary. So we weren't just restricted to doing only the ATLAS instrument science. If it made sense to combine the ATLAS instruments with others, we did.

There were four solar instruments, two that measured total solar irradiance, which is basically the integrated energy output of the sun, and two that measured solar output with spectral resolution, one in the UV and one that went from the ultraviolet (UV) through the visible and into near infrared (IR).

You can see instrument names and principal investigators (PIs) on Chart 7 (Figure 7).

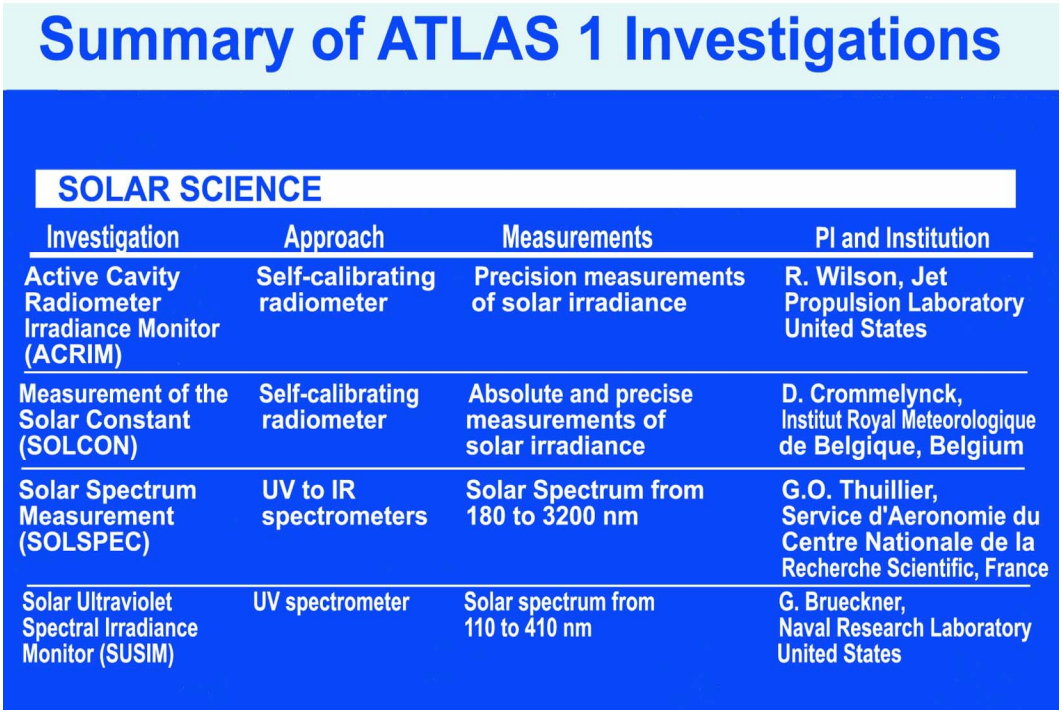


Figure 7. ATLAS-1 solar science payload.

One point to make is that the ATLAS missions, in general, were highly international. The PIs on three of the instruments, two solar and one atmospheric, came from outside the U.S., and there are a number of co-investigators from various countries. We had these little charts where you would put the flags up of the countries with PI instruments from France, Germany and Belgium, and co-investigators, variously from those countries, plus the Netherlands, plus Switzerland. On the first ATLAS we had Japan represented. I may be missing someone.

One of the things that made it fun was to work with people from so many different countries, all of whom, I think, worked together very effectively. We had that core scientific interest of looking at the forcings on the atmosphere and its response, but the international aspect was very important and I think very successful.

The ATLAS-2 mission flew just over a year later (Figure 8). This was a one pallet mission because we only had the core ATLAS payloads. We were flying with a Spartan. We still have the SSBUV. Most everything else is the same.



Figure 8. ATLAS-2 mission overview.

The only thing that doesn't show up on that chart that was nonstandard - it was a night launch; I will come back to what that did for us. The fact that we were able to get the Shuttle program to give us that night launch let us do some really unprecedented science that people are still working with today.

I mentioned in the introduction the fact that with this sort of calibration emphasis associated with being able to calibrate, fly, bring back and recalibrate, that that was a focus. If one looks at what we did for the ATLAS-2 mission, there are a number of different targets for different environmental parameters that we would try to look at and make comparisons with (Figure 9).

The Upper Atmosphere Research satellite is an ozone and UV measuring instrument that flies aboard the operational meteorological satellites that the National Oceanic and Atmospheric Administration (NOAA) provides. We had two instruments called the Total Ozone Mapping Spectrometer, or TOMS, that were flying at the time, one on Nimbus-7, which dated back to 1979. It was still flying then. The other was on the Russian Meteor-3 spacecraft, launched in 1991. We had the Earth Radiation Budget Satellite that had been flying since 1984. Also, as was mentioned this morning, the European retrievable carrier was flying at that time.

Correlative Measurement Targets for ATLAS 2

	Temp.	Ozone	Other Chem.	Total Solar Irradiance	Solar UV
Upper Atmosphere Research Satellite (UARS)	X	X	X	X	X
NOAA Operational Meteorological Satellites	X	X		X	X
Total Ozone Mapping Spectrometer (TOMS)		X	X		
Earth Radiation Budget Satellite (ERBS)	X	X	X	X	
European Retrievable Carrier (EURECA)				X	X

Figure 9. ATLAS-2 targets.

There were a number of comparable instruments on these different platforms so one could do comparisons. However, the comparisons that we were able to do this way weren't just sort of going through your whole retrieval process and coming up with an ozone profile on one, versus an ozone profile on the other. One could basically do radiance level comparisons to try to see what the instruments were doing at sort of their rawest level. So it really provided a unique way of doing these calibrations.

The next chart gives you an example of the types of things that we could do (Figure 10).

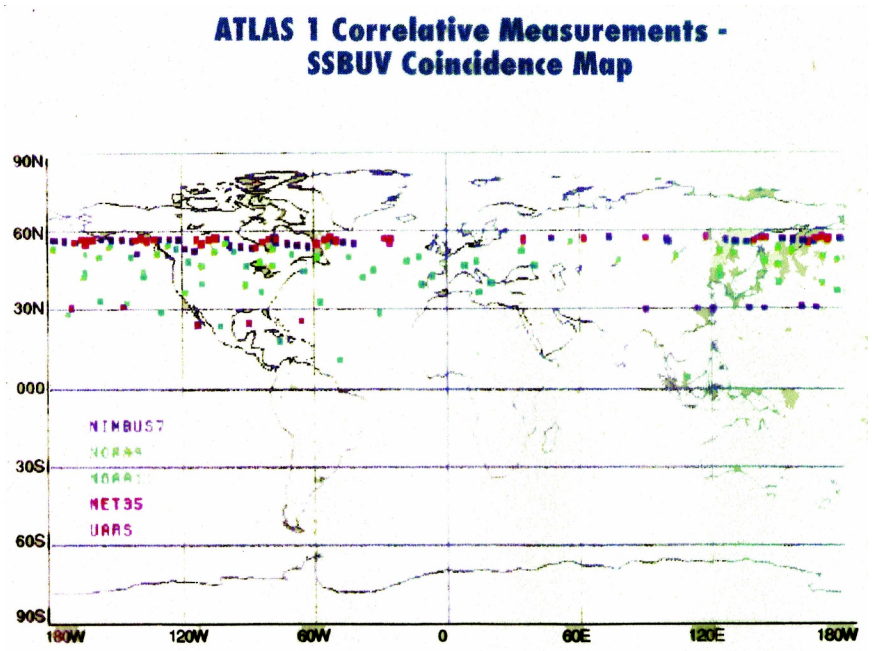


Figure 10. Example data map from ATLAS-2.

If one looked at the ATLAS-1 mission and said, how many coincidences do we have between the observations from the Shuttle and some of the other spacecraft, the different colors would correspond to different

spacecraft. These are all basically downward looking instruments that would measure ozone with TOMS or the NOAA meteorological satellites.

What you can see, especially at the highest latitude, the 57 degrees, you had a lot of coincident measurements. Then as you got away from that 57 degrees the number of coincidences were fewer.

If you think about what it takes to get a coincident measurement, a lot of times if you are interested in something like a vertical profile and want to go through the stratosphere, the only real way that you can do that is to fly a balloon. If it's a big balloon, that is hard. I will come back to this later. If it's a smaller balloon, it's not so hard.

You can see in one Shuttle mission we got something that, if you were trying to do it with balloons it would have taken many launches. In some cases, you would get data out of the open ocean where basically you have no other way of getting it. To be able to do this type of detailed comparison over a range of geographic locations is very helpful.

The third ATLAS mission was in late 1994. We flew with the German CRISTA/SPAS, which was actually a small satellite that was deployed, flew independently from the Shuttle, and was then retrieved. There was some nice complementary science. We had the SSBUV. There was also ESCAPE, a student developed and operated short wavelength UV instrument that came out of the University of Colorado. One point that I can make is I think we were all nicely integrated in a single investigative working group. The students from Colorado, in fact, were invited to the meetings and were basically treated as one of the team in terms of the mission, public relations, and such.

The scheduled launch time was just before noon. The launch time was noon. Everything else was pretty much the same. This was an 11-day mission. Here you can get a sense as to how the one pallet looked in the payload bay (Figure 11). There was the CRISTA/SPAS, which was the remotely deployed satellite; the arm, and then we had SSBUV and other things.

I mentioned that for these missions the Shuttle did the pointing. So the Shuttle attitude time line really became very central to what it was that we did. You can see on the top it shows one the things that the STS needed for things like water dumps (Figure 12).

You can see how the attitude time line was broken down. Basically, nadir viewing was for the atmospheric observations, solar viewing was for the solar observations, and there were some special attitudes designed to optimize communications between the orbiter and the SPAS satellite.

If there weren't communications, then it would have been hard to know how the instruments aboard the SPAS satellite were operating. It really is important to have some engineering data come back, especially early in the mission. I think it ended up that one was able to get better communications between the orbiter and the SPAS than was expected, but the Shuttle still ended up making a lot of maneuvers on that mission. The attitude time line really was very central to what we did.

In general, with all the ATLAS missions, the ability to have a successful mission was determined especially by the people at the Marshall Space Flight Center who were making sure that we understood all these

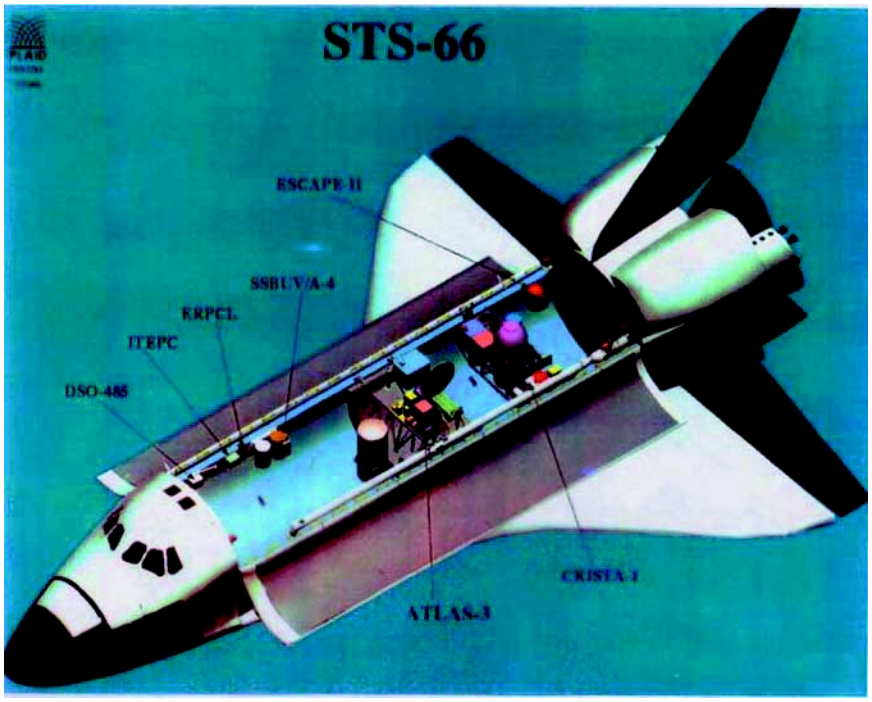


Figure 11. ATLAS pallet in the Shuttle's Payload Bay.

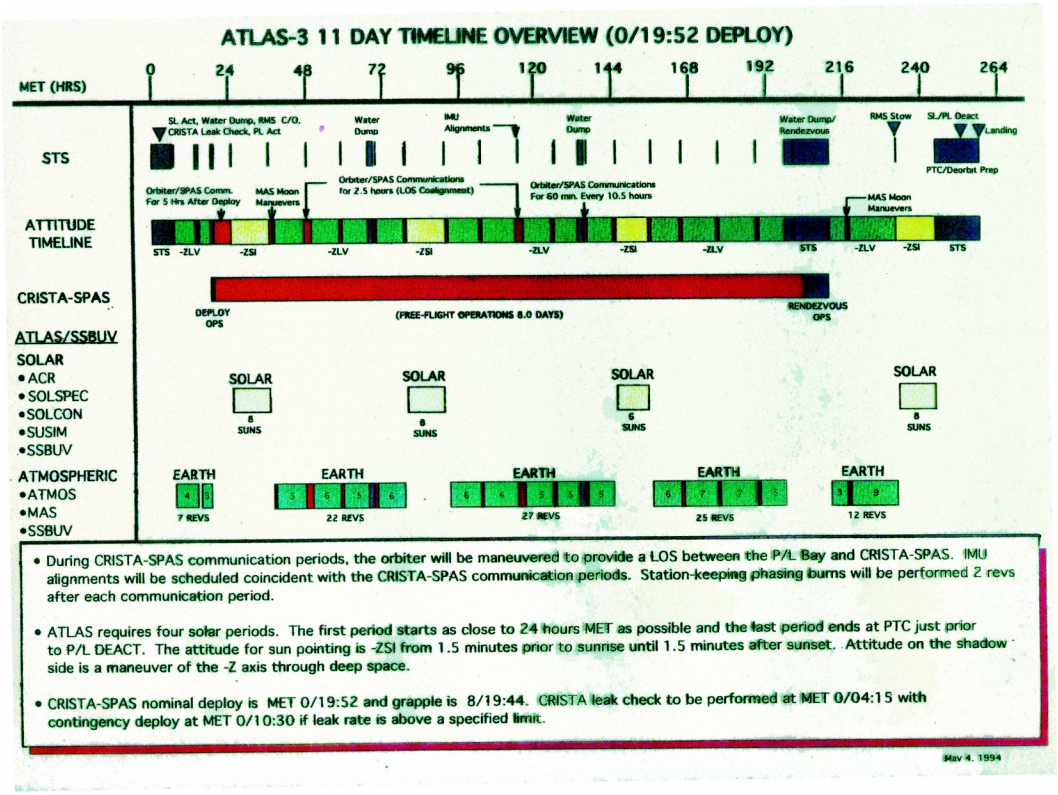


Figure 12. Shuttle attitude timeline for ATLAS-3.

things, and then they would work with the folks at the Johnson Space Center (JSC). Any sort of launch delay, or something like that, kind of means you change everything. It may be a small thing, but that could

change the Tracking and Data Relay Satellite System (TDRSS) coverage and some other things. Then, we would have to work around all these other things like water dumps.

We could not have had a successful mission without the partnership that we had with the cadre in the Payload Operations Control Center (POCC) at Marshall [Marshall Space Flight Center (MSFC)] and the people at JSC who helped us.

For me, as scientist, this leads up to the good stuff, which is some of the results. First, I just wanted to say a little bit about the Atmostphere Trace Molecule Spectroscopy (ATMOS) instrument. It is an infrared absorption spectrometer, high resolution, about 0.01 wave numbers, Fourier Transform Spectrometer, so it basically gets a whole spectra. There were a number of filters that were used. It looks at the rising and setting sun. So you basically get two observations per orbit, one at orbital sunrise, one at orbital sunset. What happens is that, depending on whether it's a sunrise or sunset, you either go from full sun to darkness or darkness to full sun. When you are looking at the top of the atmosphere, you don't see much of anything, but then as you get further down you see the effects of the absorption of all the trace constituents in the atmosphere.

What the scientists who know how to do these things can do is take that jumbled morass of lines and turn it into vertical profiles to tell how much of some molecule that you have there in the atmosphere is present at a given altitude. You get vertical resolution on the order of three kilometers. It's sort of a big data processing problem, and the scientific algorithm is challenging to take all that stuff and turn it into information, and the scientists have done that quite nicely.

As I mentioned, this instrument basically single-handedly measures more molecules than any other instrument that is flown in space, but there is a limitation: two latitudes per orbit; you don't get global coverage the way you do with some other instruments.

That is just an example of what it actually looked like to people on board as you go through a sunset event (Figure 13). You start with most of the sun up above and then you are just getting the layers. You can see the effects of aerosol layers and things like that. I'm told it's really beautiful.

This just gives you a sense of the broad range of molecules that are relevant to atmospheric chemistry (Figure 14). The measure is a function of altitude. The color gives you a sense of how well that measurement works, red being good and blue being less good. I think the main point there is that it's a lot of species, a number of which have never been measured from space by anything else. There really is enough that helps you look at whole families of chemistry.

Another point to make is that one sees a number of observations go not only from the stratosphere but through the mesosphere and into thermosphere, and in some cases we have been able to push some of those retrievals down into the troposphere. People are still doing quite a bit of unique science with these data.

This shows the spatial coverage that we have gotten over the course of the four flights (Figure 15). The first one was Spacelab-3 in 1985, where you see that there wasn't all that much compared to what we got in some of the later missions. Even so, with the only other way to make these measurements involving big,

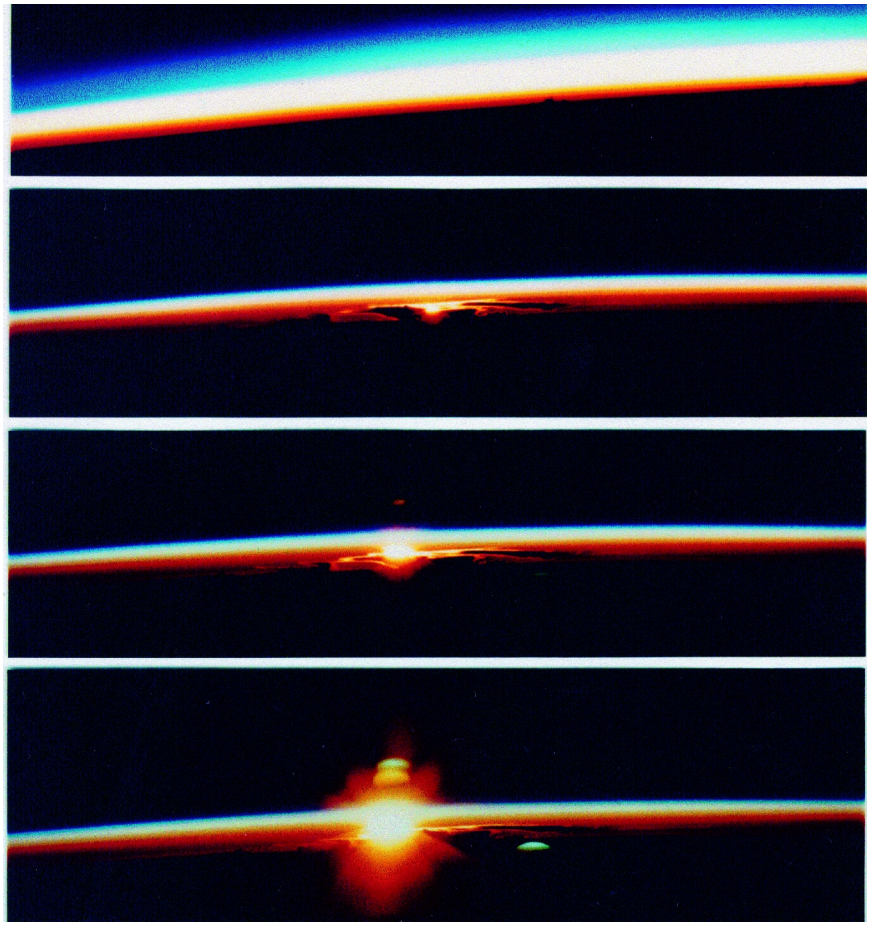


Figure 13. Sunset event from onboard the Shuttle.

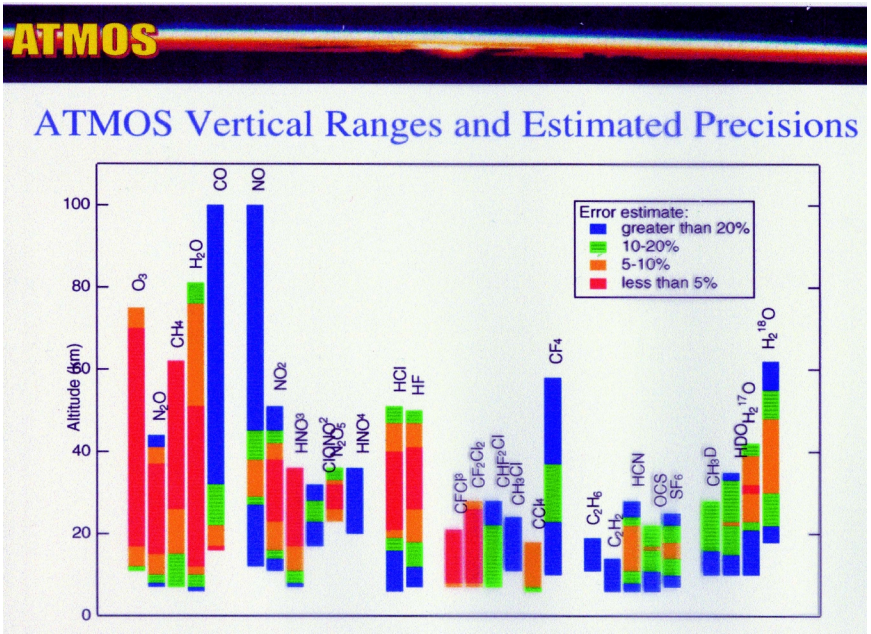


Figure 14. Example data for atmospheric chemistry from ATLAS.

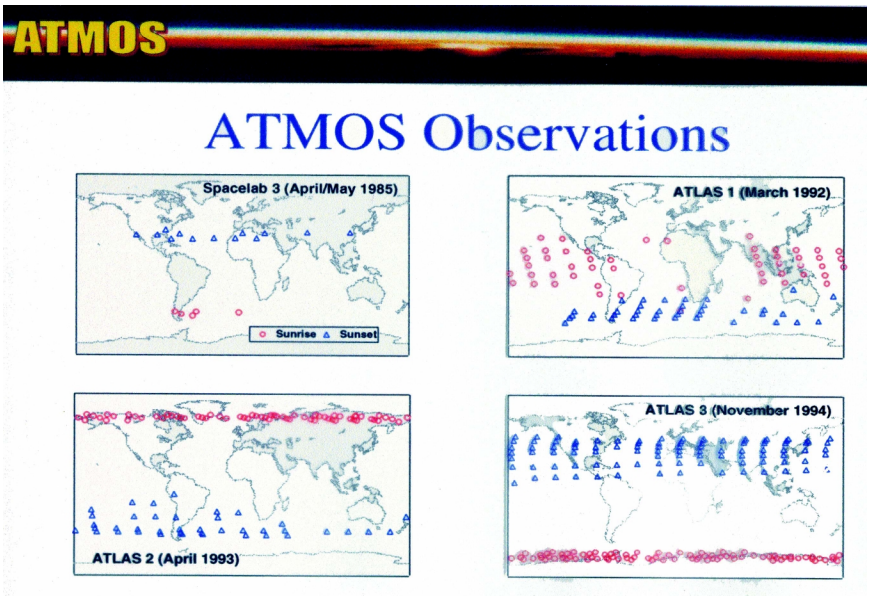


Figure 15. Instrument coverage over four Shuttle flights.

complex balloon payloads, it would have been difficult to get these measurements without the use of the unique vantage point of space.

By the way, the red is sunrise and the blue is sunset, which is of interest to chemists and probably the difference may not be that interesting to anyone else other than atmospheric chemists.

You can see that the different missions got very different spatial coverage. Some of that is the seasonal difference. Three of the four ATLAS flights were in the spring (the last was in the fall). The exact time that you launch, the orbit inclination, and the season all determine where your solar occultations will be; that is, where the sun rises and sets.

For the first ATLAS mission, launch time was relatively early in morning, and we got one coverage. The next one, which flew some two weeks later in the next year, was launched at one-thirty in the morning in order to get the sunrises at high latitudes.

The main interest there was in the springtime. We wanted to see whether there was ozone depletion in the Arctic polar vortex. We wanted see if there was something that might have looked like an Antarctic ozone hole present. In order to do that, we needed to get the sunrise observations at high latitudes, sunrise being preferential to sunset just because of the way the chemistry works.

For ATLAS-3, we wanted to get the sunrises at high latitudes in the southern hemisphere to look into the Antarctic ozone hole, especially to get these ATMOS observations to provide its full suite of molecules. That is why we had early morning launch time for one; sort of 1:30 a.m. launch time for the second; and a noon launch time for the third. The ability for us to have different launch times each time for each mission was critical to us in being able to get the science that we wanted.

Next I'll show a couple of scientific examples. This is what we call a "spaghetti" diagram (Figure 16). It shows the vertical profiles of the concentrations of a number of species important to atmospheric chemis-

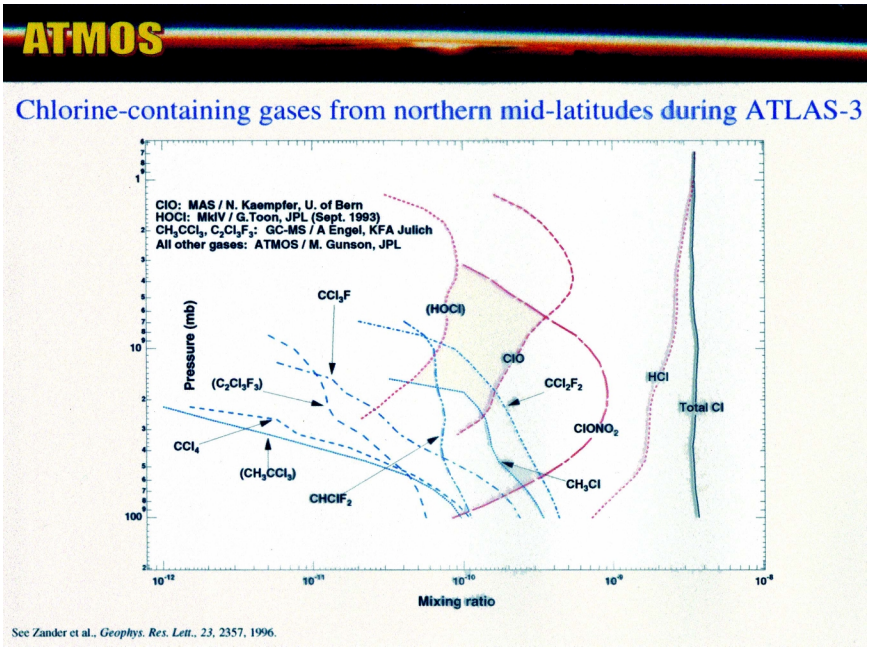


Figure 16. ATLAS-3 chlorine data.

try. These are all chlorine-containing gases, chlorine being of interest because of industrial production of chlorine and those chlorine compounds get into the atmosphere and, ultimately, lead to ozone depletion.

The question becomes, how much chlorine is in the stratosphere and where does it come from? We think we understand because we know what the natural sources are; we know what the industrial sources are. We know what happens to chlorine when it gets into the stratosphere. The big compounds get broken up by UV radiation and the chlorine ends up in what we call reservoir species.

The question is always asked of us, how sure are you that you really know? Can you convince us that there are no missing sources, that chlorine from sea salt in the ocean doesn't get up to the stratosphere, or chlorine from swimming pools, or whatever?

What this diagram shows is that we actually were able to measure most all the significant chlorine-containing compounds in the stratosphere. When one adds them up all up, weights them by the number of chlorine atoms, and one sees very good consistency between 100 millibars pressure, which is about 15 kilometers, and the top of the stratosphere about 50 kilometers up.

What that says is that it helps convince us that our understanding of the chlorine budget of the stratosphere is well understood. Also, because we have the Montreal Protocol on Substances that Deplete the Ozone Layer, it helps convince the policymakers that the scientific rationale for regulations that have been written were on a firm footing. This was done preliminarily from the Spacelab-3 mission, but this chart comes out of the third ATLAS mission. In terms of supporting the international assessment process and convincing people that what we say is really right, these results were very important.

The next chart gives some sense as to the long-term evolution of the halogen budget in the stratosphere (Figure 17). What this does is look at the hydrogen chloride and hydrogen fluoride at 50 kilometers

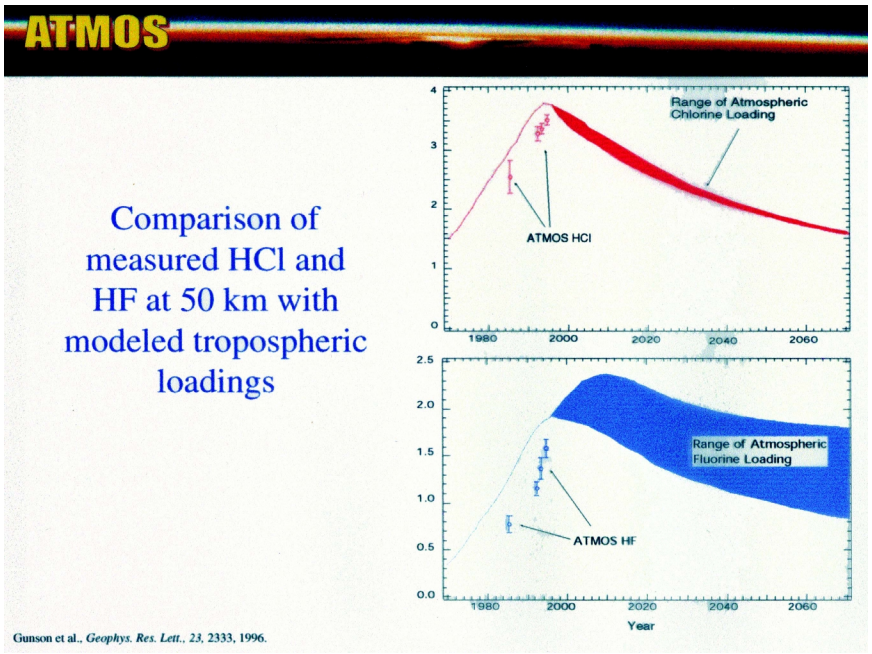


Figure 17. Long-term halogen development data from ATLAS.

because those two molecules are basically the ultimate repository of chlorine and fluorine, respectively, in the stratosphere. They get into the stratosphere mainly through chlorofluorocarbons, especially fluorine where there is almost no natural source of fluorine in the stratosphere.

You can see the Spacelab-3 data from 1985, and then ATLAS-1, 2 and 3 from 1992, 1993, and 1994, and see what that increase is. This is something that really could not be done from the ground. If you try to do it from the ground, you can only measure a total column. That is basically an integral between the observatory where your instrument is and the top of the atmosphere.

But this is at 50 kilometers. Pretty much there are none of what we call "source gases" left. All the chlorflurocarbons (CFCs) are photolyzed. If there is chlorine in the stratosphere at 50 kilometers, it's as hydrogen chloride (HCl); if there is fluorine in the atmosphere at 50 kilometers, it's hydrogen fluoride (HF).

What you can see if you look at it, say for the case of chlorine, you've gone in about nine and a half years from about 2.7 to about maybe 3.6 parts per billion, about a one-third increase. If you look at HF, you've gone from about 0.8 to about 1.7 parts per billion. So in this nine and a half years, the ATMOS is very clearly demonstrating that at 50 kilometers up the fluorine content of the stratosphere has doubled. And that, as we can show through comparisons to surface level CFC measurements, together with atmospheric models, is because of increases in industrially produced source gases. So the ATMOS data have been very crucial in helping us to convince policymakers that the science that we say is correct.

The next chart has some of the highlights from the Millimeter Wave Atmospheric Sounder (Figure 18). One can look at the chart and see that there is a range of information.

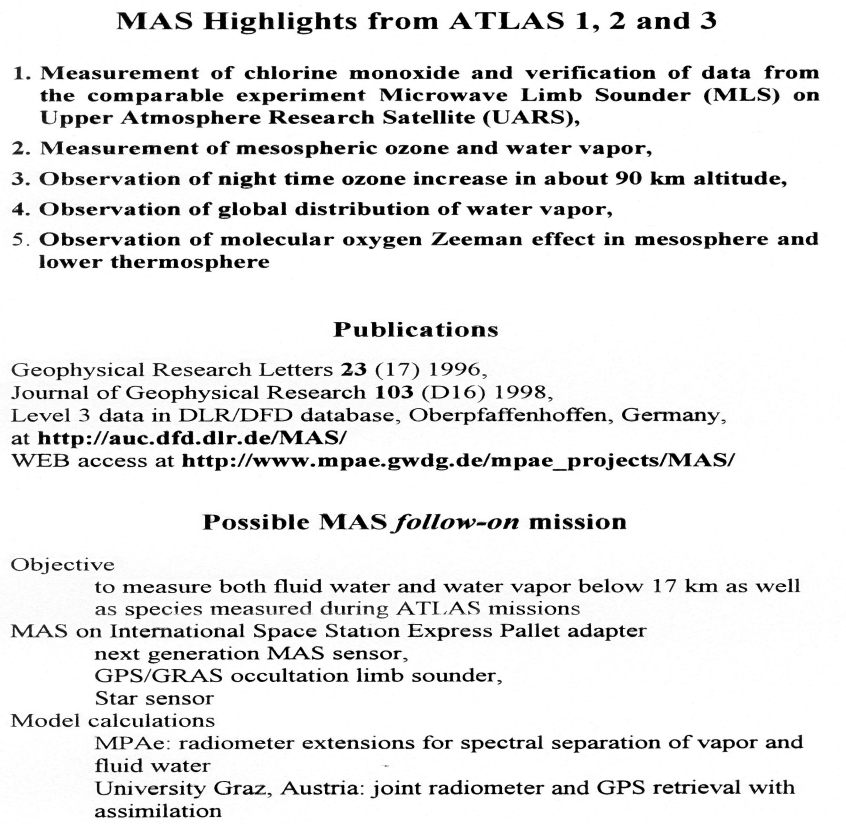


Figure 18. MAS highlights from ATLAS.

One of the things that is worth pointing out is that it's not really just what they did for the stratosphere. One of the unique things about the MAS instrument was that it had high spectral resolution, which is very good at looking higher up in the atmosphere, in the mesosphere, and lower thermosphere because of the way that lines are broadened. The higher up you go, the narrower the spectral lines get and the more powerful that high spectral resolution is.

If one actually looks at it from what we would consider as a highlight in the Office of Earth Science, there may not have been that much because we also had a similar instrument flying on UARS which had nine months of global data at this point. But, in terms of mesospheric and thermospheric science, the ability to study some fairly subtle things with high spectral resolution led to unique science that has yet to be duplicated from space.

The next topic is some of the results from the solar instruments.

We compared the UV spectra obtained from the SOLSPEC instrument, which is one of the ones that flew aboard ATLAS with similar instruments from ATLAS/UARS. If one plots the measured irradiance as a function of wavelength on a logorithmic plot, one sees that the curves are in agreement within the thickness of the lines.

There were different kinds of instruments on different platforms, one of which had been flying for seven months. If one goes back historically, the ability to get absolute calibration for space-bound UV instru-

ments was quite limited. I think this was a demonstration of how far we have come as a community in being able to do what we say we are going to do and do it with stated accuracy.

The next chart does a similar comparison to the three UV instruments that flew on the first ATLAS mission (Figure 19). They are supposed to be in different colors. The international nature of the mission is demonstrated by the labeling on the charts, in fact. You can see that with the exception of some small wiggles, especially near 250 nanometers, that within the thickness of the lines there was excellent agreement between all three instruments. If one went back probably ten years before, if someone could do 20 percent at those wavelengths, they were happy. They were doing a couple of percent.

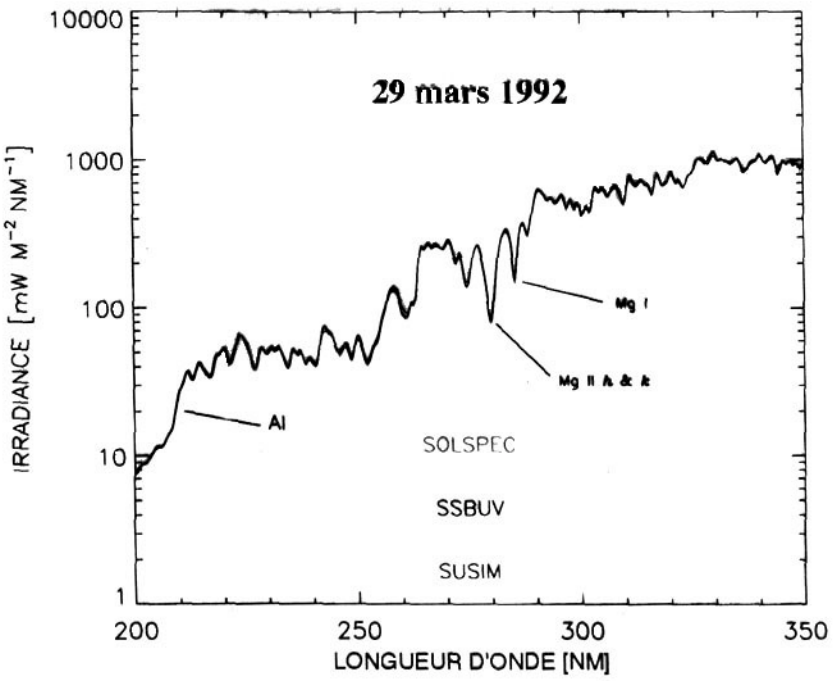


Figure 19. UV data from ATLAS-1.

LITE was the Lidar In-space Technology Experiment. That was really the first space-based demonstration using an active remote sensing laser to try to study clouds and aerosols in the Earth's atmosphere. You can see some of the highlights of it, and the mission is described a little more clearly on the next viewgraph (Figure 20).

What you have is the Shuttle flying while moving at about seven and a half kilometers per second. You shoot a laser pulse down and then you can get a return from clouds, from aerosols, or the ground. The amount of time between the time the laser fires and the time the signal comes back tells you how far it is. The intensity gives you a sense of how much is there. Then you are flying along, basically getting not quite every kilometer; you are getting a sample which is averaged over about a quarter of a kilometer.

If you think about what lasers tend to do for you, you get a small divergence, so you get a small footprint. That's good. The short pulse length corresponds to range resolution. The wavelength used, basically one micron, meant that it was very appropriate for looking at clouds and aerosol particles, and by having a specific wavelength one could discriminate against noise.

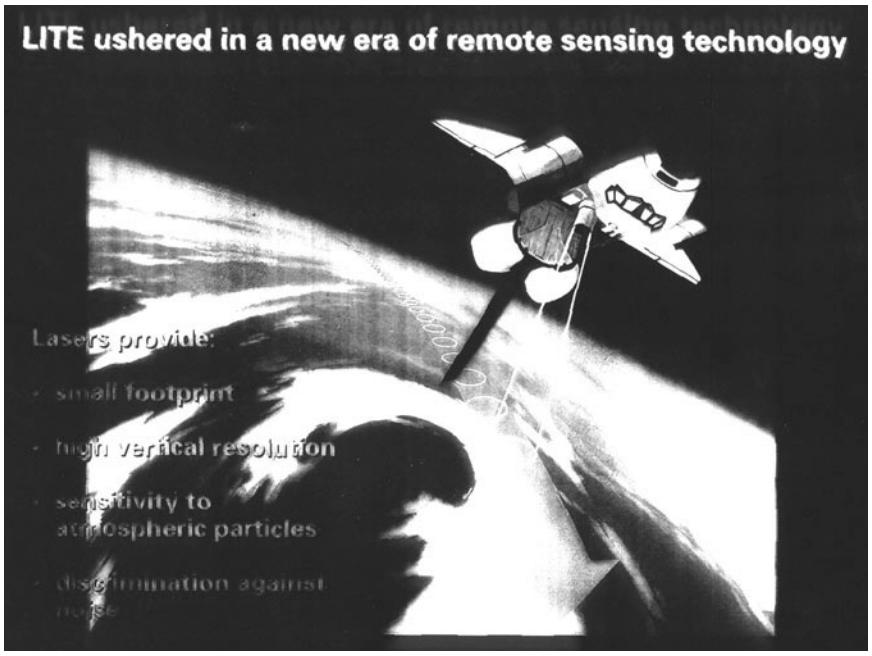


Figure 20. LITE overview.

This flew on the STS-64 mission in September of 1994 (Figure 21). It was a 57-degree orbit. Again, one can see that one was able to do this type of unique science but still have a number of other things going on, including a Spartan that was deployed and retrieved. They got about 45 hours of data. The Spacelab hardware really provided a lot of the engineering services. When I talked to the PI because I wasn't even

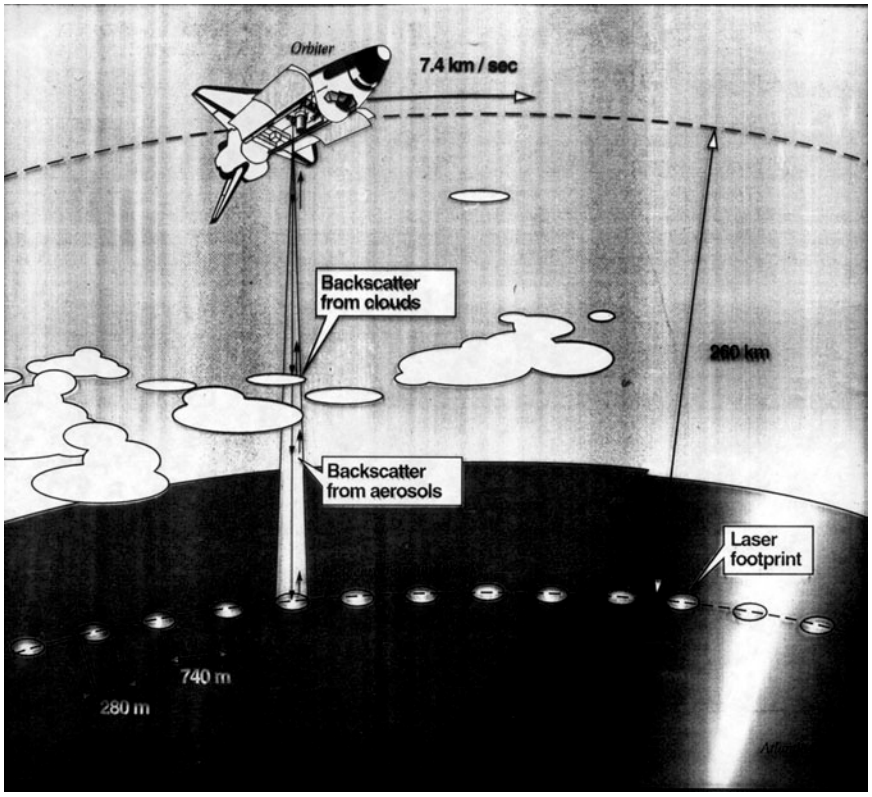


Figure 21. Artist's concept of LITE from orbit.

sure this was a Spacelab mission, he said the fact that Spacelab was there meant that he really only had to worry about his instrument because so many of the engineering services they needed were provided through Spacelab.

This next chart gives a sense over the course of the mission the ground tracks that they got (Figure 22). It wasn't 100 percent duty cycle, certainly, but over the course of the 8-day mission at 57 degree orbit that's a lot of observations of clouds and aerosols.

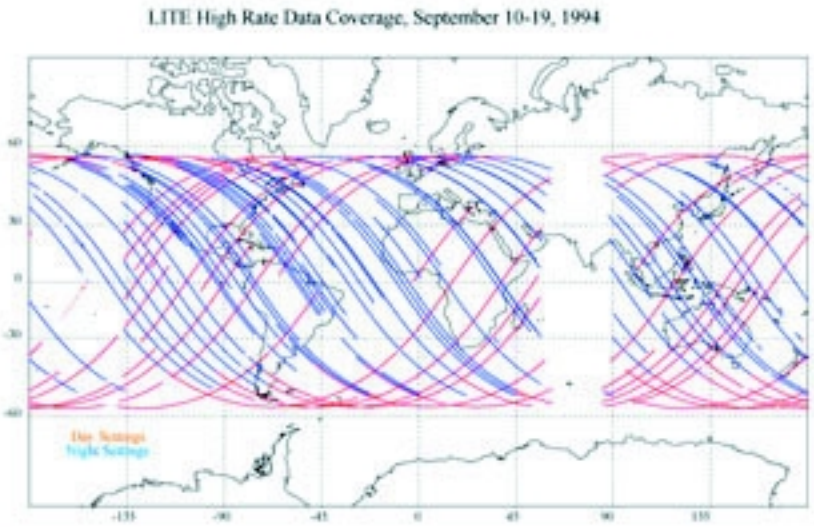


Figure 22. LITE high rate data coverage.

This really was something that people had never had from space before. People have done lidar from aircraft, but if you think about how many aircraft flights it would take to do that, it's an awful lot. So this was a great demonstration. It was constituted as a technology experiment, but as I will show you, there was some incredibly beautiful science that came from it.

This is a series of these observations (Figure 23). It's a false color image of the strength of the returns. The top shows you where LITE was flying over, the abscissa gives a measure of location in latitude and longitude, and the color gives you a sense of the strength of the return — white being high and the blue being background.

What you can see is sort of the diversity in clouds as it was flying along the track, including, in some cases, if the clouds weren't that thick, one could actually see multiple cloud levels. You could look right through one cloud, get some sense as to how thick and how intense it was, and then see another cloud layer beneath it. That is something that with the sort of the standard passive types of remote sensing is very hard to do.

With most passive techniques, you can't see beneath a cloud, but the lidar could actually make it through some clouds into the next cloud, and sometimes all the way down to the surface with very accurate vertical resolution.

The next chart is an example of looking at super typhoon Melissa that was out over the Pacific Ocean (Figure 24). This was sort of serendipity: (a) that the typhoon was there and (b) that LITE actually flew

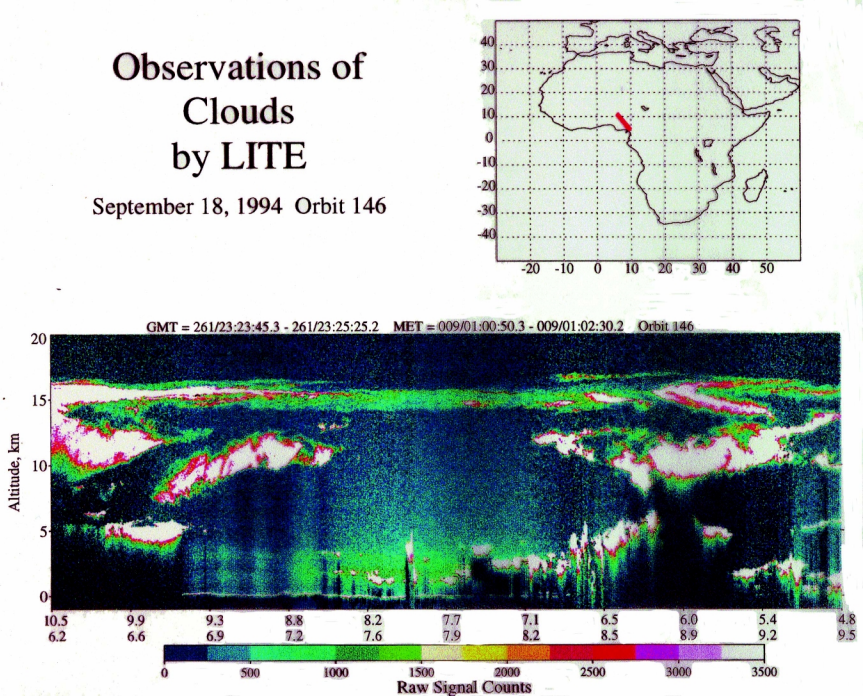


Figure 23. Cloud observations by LITE.

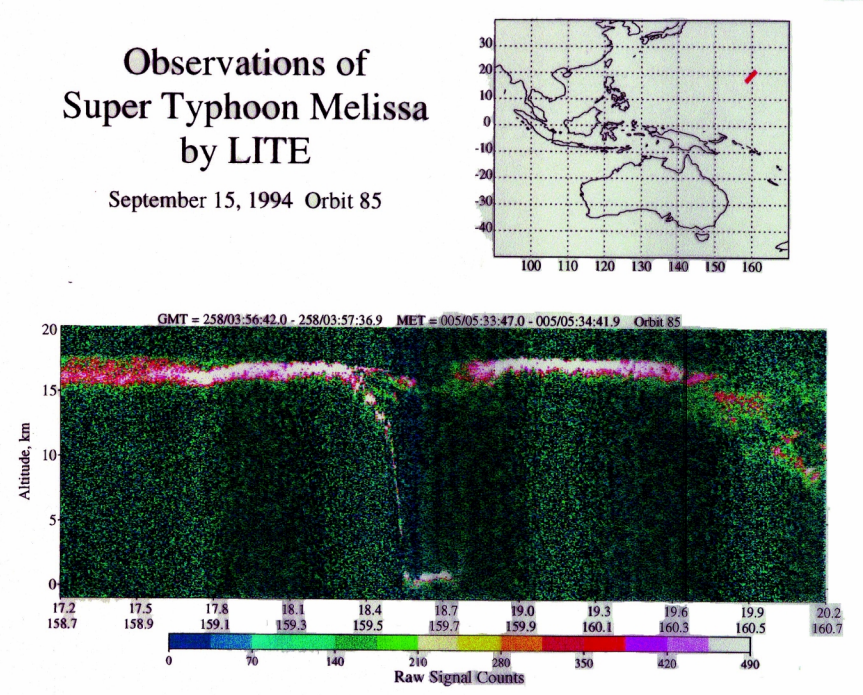


Figure 24. Observations of Super-typhoon Melissa by LITE.

right over it. These measurements were made in bright daylight, so the plot appears a little speckled. One can see the high altitude clouds around the eye with a top height of about 16 km. The clouds are very thick. Then as you get over the eye, you can see down to the surface of the ocean. In some cases there is a light

cloud near the top and then you are getting a return from the surface, and then you could see the clouds. I think this was just wonderful. There is maybe not too much quantitative data here, but I think this really helped people appreciate the power of the technique.

The next figure shows continental haze over the U.S. (Figure 25). One sees, in some cases, there are clouds; in other cases, you see it looks like about one and a half or two kilometers of haze layer near the surface, and then depending on where you are, the height of that is greater or less. That is the continental haze. Since it is northern fall, you are probably looking at a little bit of photo chemical haze, and sulfate aerosols.

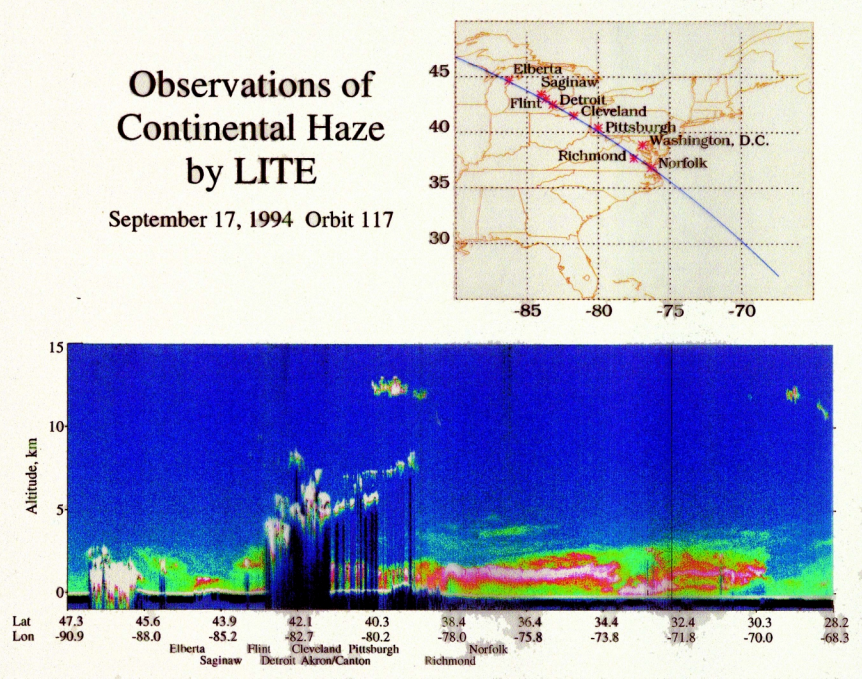


Figure 25. United States continental haze observed by LITE.

The next chart shows Saharan desert dust (Figure 26). One sees, at about three kilometers, a layer of Saharan desert dust. One can actually look out and watch the stuff getting transported. In some cases it will cross the Atlantic Ocean, and end up in the Caribbean and even deposit dust over Florida. To be able to get this resolution is very important.

There is some nice complementary science done with the passive sensors, which sometimes, for things like aerosol layers, really helps to know where they are. This gives us that type of information.

The last chart shows biomass burning over South America (Figure 27). One can see the plumes low down, and then you can see how things are evolving over the course of the distance. There you've got some clouds above. Again, you have these things where you are looking at clouds up near 15 kilometers, but you can see through them, and then you are seeing the aerosol layer, which basically pretty much never gets above 5 kilometers. It's the unprecedented nature of the height information and being able to look at multiple layers that make these data so intriguing.

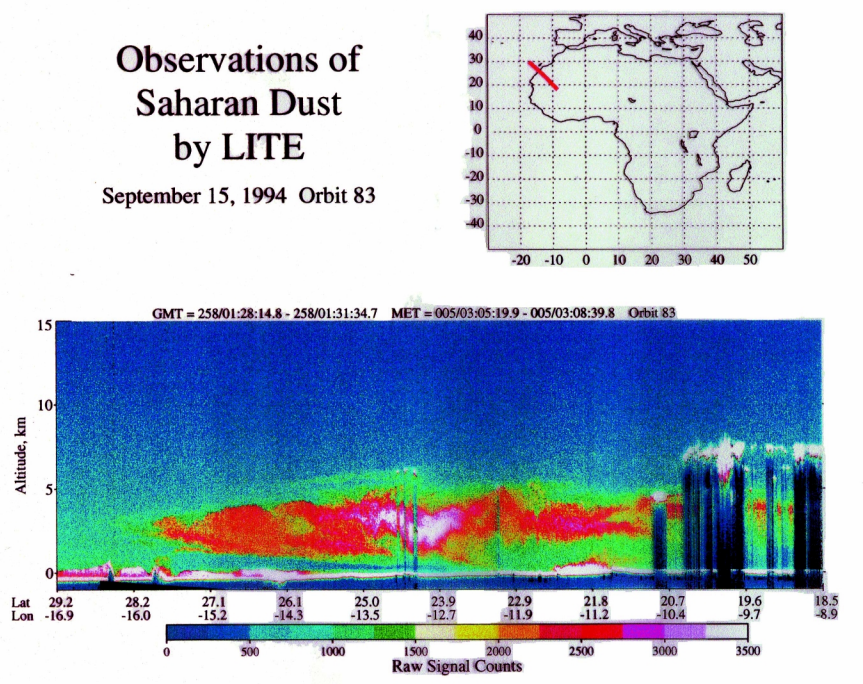


Figure 26. Saharan dust observations by LITE.

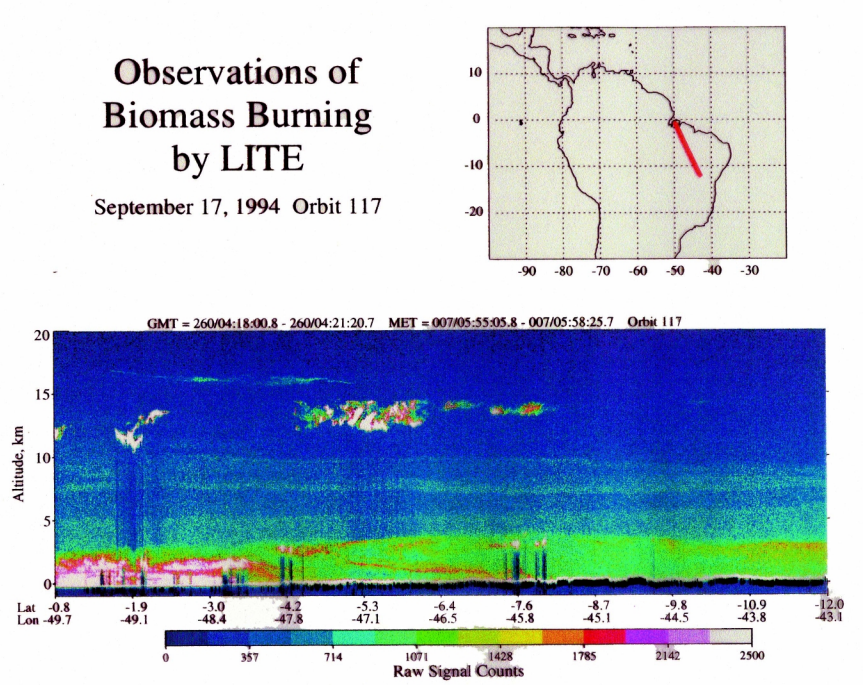


Figure 27. Biomass burn plumes over South America.

To summarize the LITE mission, I think it really demonstrated the utility of spaceborne lidars to provide crucial cloud, aerosol, and surface data. The experience gained will help ensure the future of spaceborne lidars.

I think one of the clearest demonstrations of the effectiveness of doing science this way, with doing this 8-day demonstration, was that through a competitive process we recently selected as one of the latest rounds of Earth System Science Pathfinders, something called PICASSO-CENA. It's a joint U.S.-French collaboration where we will be using similar techniques, active remote sensing with lidar to look at clouds and aerosols. We will be combining it with passive remote sensing.

I think the ability for the scientists involved to be able to get a mission like this through a competitive peer-reviewed process was helped immensely by the fact that one had this very successful demonstration aboard the Shuttle using the Spacelab hardware.

We've got another instrument that was selected through the previous Earth Systems Science Pathfinder, called "vegetation canopy lidar." This is a lidar that will be used to try to study aboveground biomass. That was demonstrated through another Shuttle lidar instrument that didn't fly in the Spacelab mission, but flew in the GAS can.

I think one of the things that we have learned is that these short demonstrations, and the Spacelab hardware was very helpful in doing this, helped make the case for the future longer term missions that we do.

One other point that I do want to make is one lesson that I learned from involvement in this. Through the help of everyone involved in Spacelab and Shuttle when we were doing Earth science from these Shuttle missions, some marvelous opportunities for education and outreach were provided. We had a lot of support from the crew. For the first ATLAS mission we had a poster, we had a slide set, we had a video that the crew helped with. We had teachers' guides. For ATLAS-2, we actually had bilingual teachers' guides. We took some of the stuff from the first one and actually did Spanish language versions of it.

These Spacelab missions not only provided wonderful science, but they provided marvelous opportunities to help communicate our message to the public and to students. It was one of the things that made it so much fun.

I hope that I gave you a flavor of how we were able to do what I think is world-class science from the Shuttle, where the Spacelab hardware fit in, and how so much of it was letting the experimenters not have to worry about all these other services.

I think a number of things that we did were wonderful. As I indicated, they were fun. I think it clearly demonstrated the way that the NASA system, Houston, Marshall, and the working groups all were able to come together to do some fairly complex things that have stood the test of time.

With that, I will stop.

Space Sciences
Dr. Arthur Davidsen

I'd like you to turn your attention away from the Earth now for a few minutes and out into deep space. I'm going to talk to you about the Astro missions.

There were two missions, Astro-1 on Columbia in 1990, a 9-day mission, and Astro-2 on Endeavor in 1995, a 16-day mission (Figure 1).

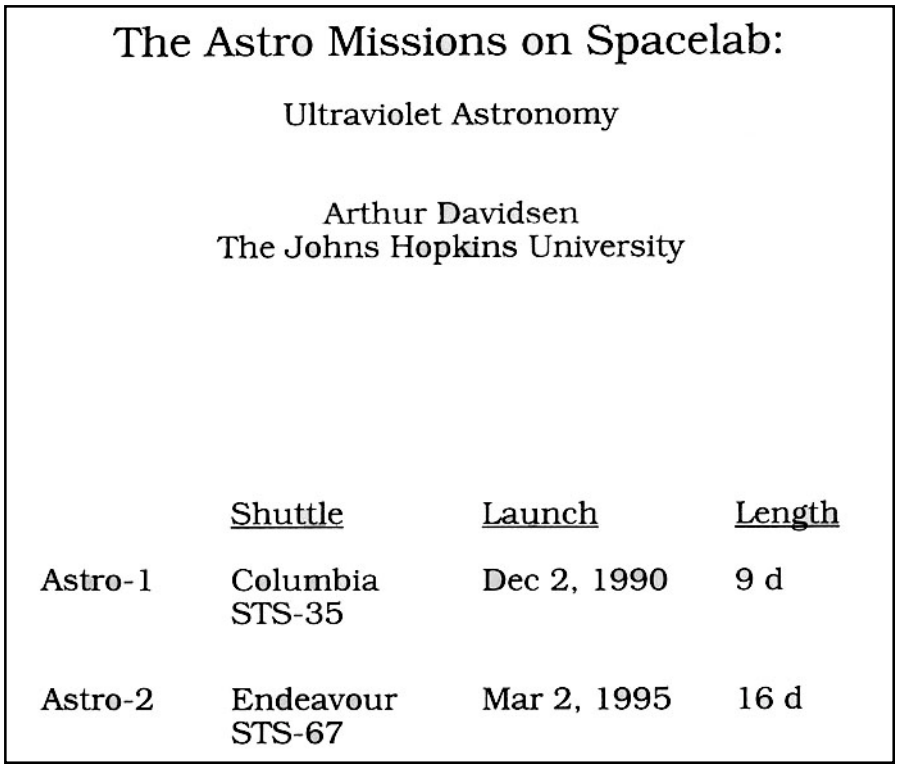


Figure 1. Spacelab ASTRO missions.

The length of the mission is certainly important for astronomy because we want to look at a lot of different objects, but also we want the maximum amount of exposure time in order to collect data. Astro-1 was not long enough to accomplish everything we wanted to do, but Astro-2 was long enough to be very successful.

The Astro instruments and their Principal Investigators (PIs) are listed here (Figure 2). There were three ultraviolet telescopes mounted on the IPS, a European instrument pointing system that had previously been used once on the Spacelab for observing the sun. On Astro-1 it was used for the first time to observe stars at nighttime.

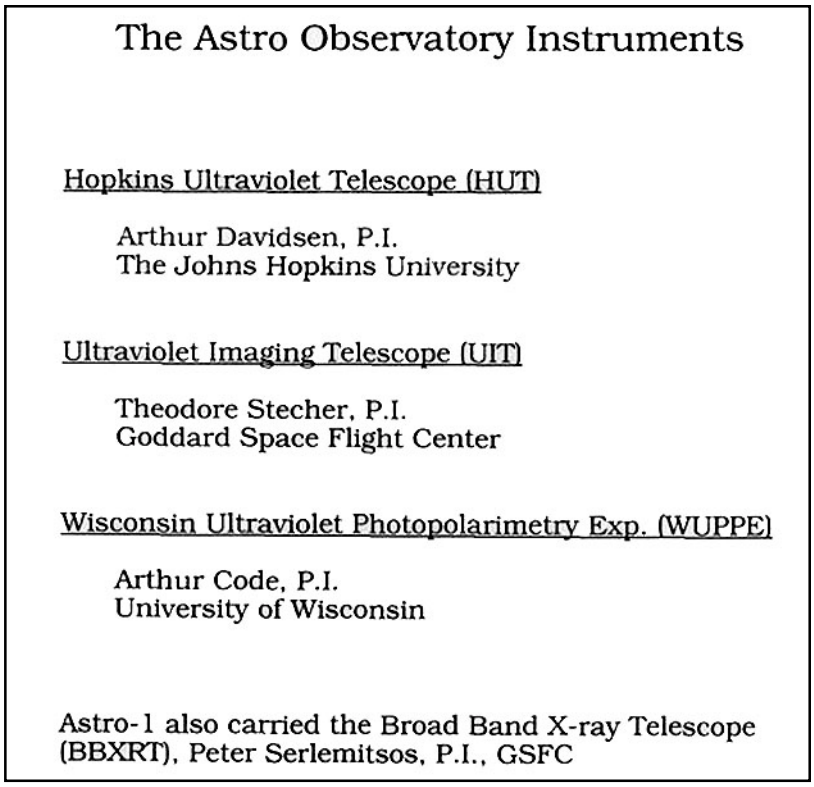


Figure 2. ASTRO instrumentation.

The instruments included the Hopkins Ultraviolet Telescope (HUT), the Ultraviolet Imaging Telescope (UIT) from Goddard, and the Wisconsin Ultraviolet Photo-Polarimetry Experiment (WUPPE). On Astro-1, there was also an x-ray telescope that had been added by NASA, the Broad Band X-ray Telescope (BBXRT) from Goddard Space Flight Center.

I will give you an overview of the missions and some highlights from the ultraviolet Astro instruments, and then concentrate on one particular piece of science that we carried out.

The functions of the three ultraviolet instruments were all different but complementary (Figure 3). HUT performed spectrophotometry at very short ultraviolet wavelengths, what we call the far ultraviolet, between 900 and 1200 angstroms in particular. There had been very few measurements in this spectral region prior to Astro-1. Designed especially for faint object, HUT could be used to study nebulae, galaxies and quasars, in addition to various kinds of stars.

UIT's goal was to employ a very large field of view so that it could photograph a relatively large region of the sky and cover an entire nearby galaxy in one picture. This can't be done with the Hubble Space Telescope, for example. Hubble has a very small field of view so it can bore in on the distant universe, but it really can't look at whole galaxies up close.

Then WUPPE, providing polarization measurements throughout the ultraviolet band, was also a new capability that didn't exist prior to Astro. It was limited to observing primarily fairly bright starts.

Some characteristics of the Astro instruments are listed in Figure 4 (Figure 4).

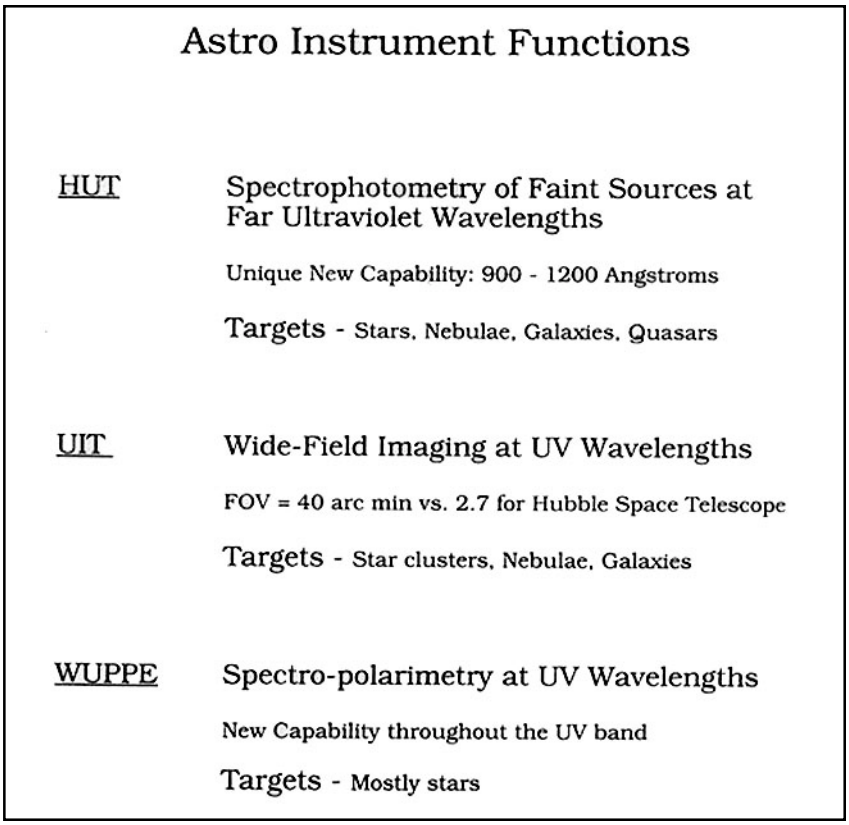


Figure 3. ASTRO instrument functions.

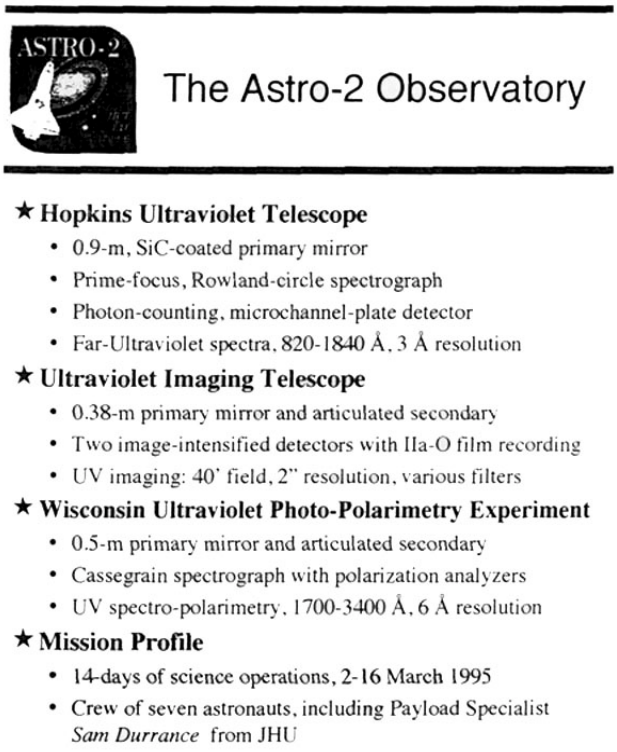


Figure 4. The ASTRO-2 observatory instruments.

You heard a lot about the history of Spacelab this morning. It was a long history. It was a long history for ASTRO as well (Figure 5). We were selected from that AO in 1978 that was mentioned earlier today. We had an initial projected launch date of July 1, 1983.

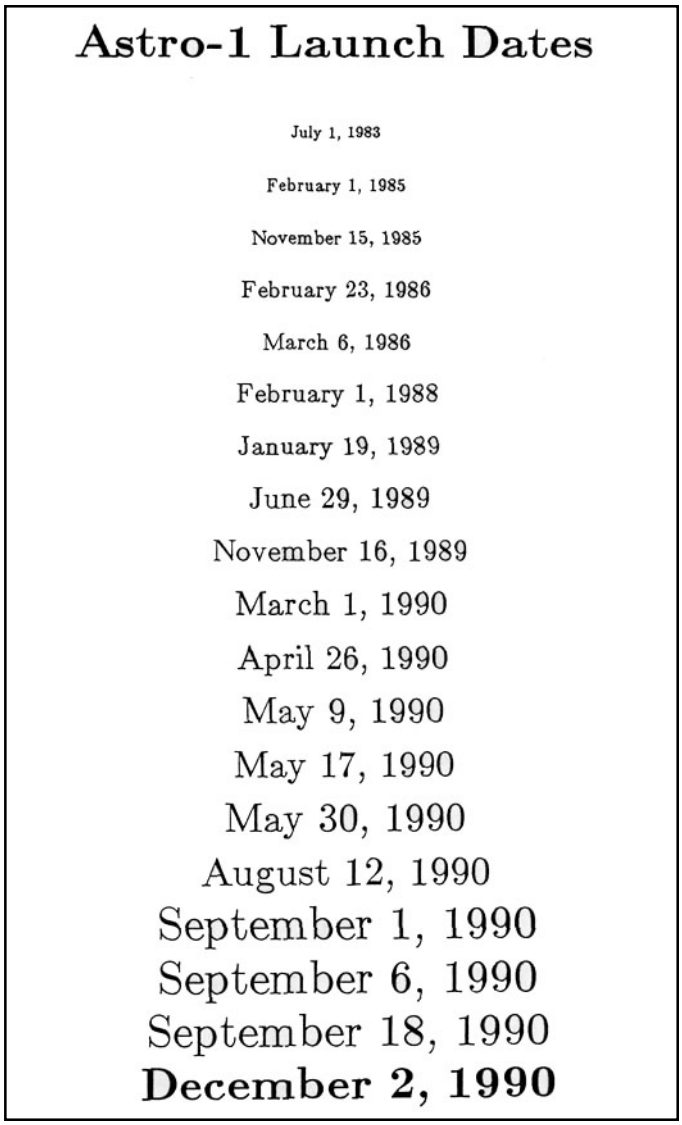


Figure 5. ASTRO launch date history.

As time went on, the launch date slipped a bit, and moved all the way to March 1986. That launch was scheduled to coincide with the passage of Comet Halley through the inner solar system. We were going to try to get simultaneous observations from the Shuttle along with the fly-by missions that were occurring at that time. Of course, the Challenger accident put an end to that. We were scheduled to be the next mission after Challenger. We were actually ready to go in the Columbia when that happened.

The Challenger tragedy of course produced a further delay for Astro, as it did for everybody, first to 1988 and then to 1989. Finally, the frustration really hit us in 1990. That was the year when the Shuttle suffered from a series of hydrogen leaks that postponed our many launch attempts. I think Astro-1 must hold the

record for the largest number of official launch dates of any mission ever. Ultimately, though, Astro-1 was a great success scientifically.

Astro-2 was even more successful because of teh amount of data we were able to collect in a much longer mission (Figure 6). There were 385 different pointings during the Astro-2 mission. The entire mission was dedicated to astronomy, of course. We had four astronomers on board, two payload specialists from the instrument teams and two mission specialists, and they worked very effectively with the telescopes around the clock.

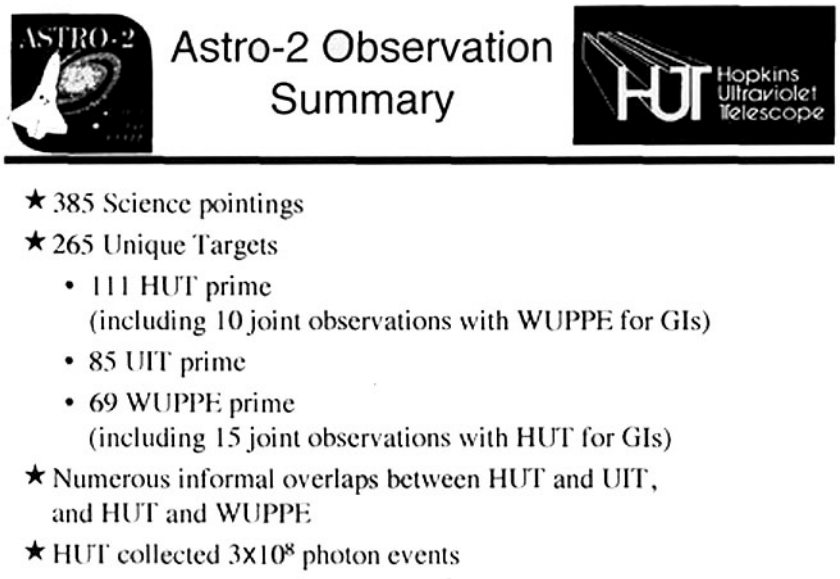


Figure 6. ASTRO-2 observation summary.

We looked at 265 different objects in the course of this mission. Specific objects of interest were selected by each of the teams. In some cases we were all interested in the same objects, but some were more interesting than others to each team. In any case, simultaneous observations were carried out by all three instruments whenever possible.

The proof is in the publications. Here I've summarized the output from Astro (Figure 7). The numbers reflect refereed publications and major journals - the Astrophysical Journal, the Astronomical Journal, Science, and Nature. A total of 167 paper have been published so far, and there are still papers being written. I think that is an impressive record for two space shuttle missions.

There was a whole issue of the Astrophysical Journal Letters dedicated to the results from HUT on the Astro-2 mission (Figure 8), and likewise, the UIT had an issue dedicated to their papers from the Astro-1 mission (Figure 9). A great deal of science was conducted with Astro. I won't be able to tell you about most of it today, but will just touch on some examples and highlights.

Publications in Refereed Journals

	Astro-1	Astro-2	Total
HUT	36	49	85
UIT	29	20	49
WUPPE	19	14	33
Totals	84	83	167

(and more in press or in preparation)

Journals

Astrophysical Journal (most papers are here)
Astronomical Journal
Science
Nature
Publ. of Astron. Soc. Pacific
Monthly Notices Royal Astron. Soc.

Figure 7. ASTRO publication summary.



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THE ASTROPHYSICAL JOURNAL

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HOPKINS ULTRAVIOLET TELESCOPE
ASTRO-2 MISSION

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Figure 8. Astrophysical Journal issue dedicated to HUT findings from ASTRO-2.



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LETTERS

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ULTRAVIOLET IMAGING TELESCOPE OBSERVATIONS OF THE CRAB NEBULA *Gregory S. Hennessy, Robert W. O'Connell, Kwang P. Cheng, Ralph C. Bohlin, Nicholas R. Collins, Theodore R. Gull, Paul Hintzen, Joan E. Iannone, Wayne B. Landsman, Morton S. Roberts, Andrew M. Smith, Eric P. Smith, & Theodore P. Stecher*	L13	144-E5
AN ULTRAVIOLET IMAGING TELESCOPE STUDY OF THE GLOBULAR CLUSTER M79 (NGC 1904) *Robert S. Hill, Jesse K. Hill, Wayne B. Landsman, Ralph C. Bohlin, K.-P. Cheng, Paul M. N. Hintzen, Robert W. O'Connell, Morton S. Roberts, Andrew M. Smith, Eric P. Smith, & Theodore P. Stecher*	L17	144-F1
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ASJOAB 395 (1, Pt. 2) L1-L54 (1992)

Figure 9. Astrophysical Journal issue dedicated to UIT findings from ASTRO-1.

Let me begin by telling you a little bit about some highlights from WUPPE (Figure 10). First of all, WUPPE vastly increased the total database on UV polarimetry, from just two stars that had been measured in balloon flights to 32 stars that WUPPE managed to observe on Astro-1.

Figure 11 is an indication of that (Figure 11). The balloon data are for two stars showing the percent polarization over some fairly broad wavelength ranges in the near ultraviolet, where balloons are sufficient to gather data. On the other hand, WUPPE provided a stack of many, many stars with polarization data as a function of wavelength throughout the ultraviolet. It was an enormous increase in the available information in this area of astronomy.

On Astro-2, WUPPE increased the volume of polarization measurements even more — drastically, in fact. The WUPPE team had 75 of their own targets plus 161 others for UIT or HUT. They ended up with targets essentially all over the sky (Figure 12). This allowed them to measure polarization of lots of different kinds of stars, but also the interstellar polarization produced in gas and dust between the stars - which was one of their major interests - in many different directions throughout the galaxy.

Sample of Highlights from WUPPE

1. WUPPE vastly increased the quantity of UV polarimetry with Astro-1 from 2 stars to 32 stars

2. Distribution of Astro-2 observations with 75 WUPPE targets and 161 other targets

3. Typical interstellar polarization observed toward the star alpha Cam with WUPPE and in the optical band

4. UV and optical polarization of several stars compared with an empirical fit (the Serkowski curve)

5. UV polarization in the Be star Zeta Tau provided a surprise compared with expectations

6. Visible light and UV polarization of Mars -

The visible light is reflected from the planet's surface
The UV is scattered by the Martian atmosphere

Figure 10. Sample highlights from WUPPE.

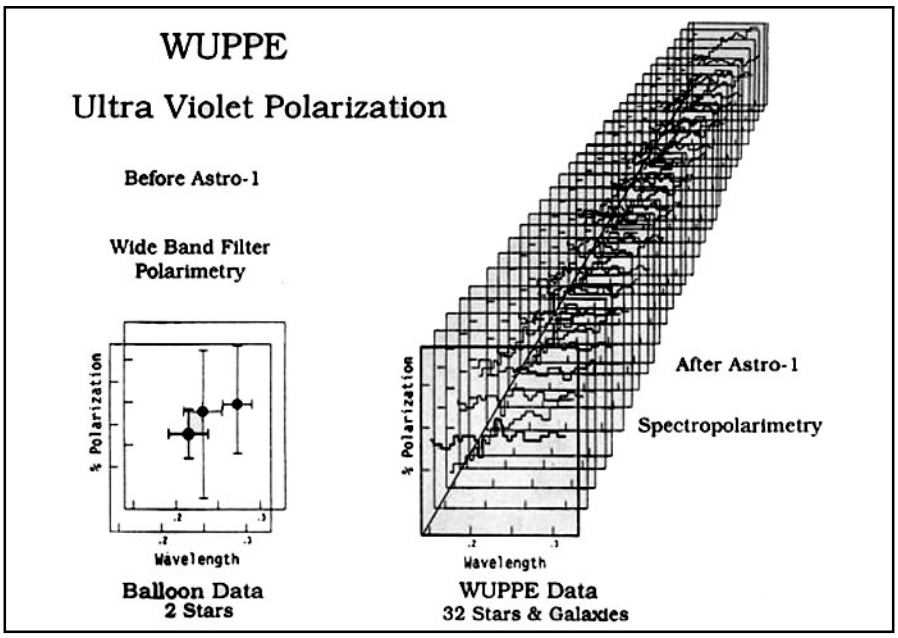


Figure 11. Comparison of data from balloon flights (left) and WUPPE (right).

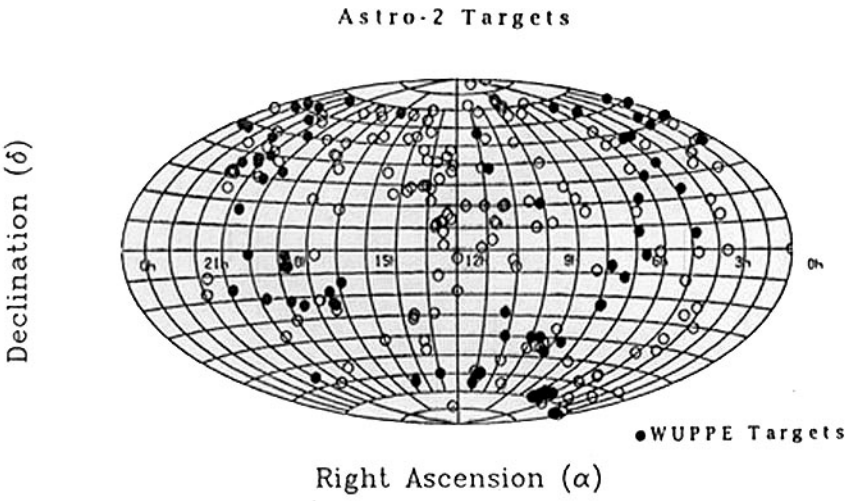


Figure 12. Graph of ASTRO-2 observation targets.

Figure 13 shows the typical interstellar polarization for a particular star, Alpha Cam, between the ultraviolet and the optical (Figure 13). The top graph is the flux as a function of wavelength. The WUPPE ultraviolet data is on the left, and the ground-based optical data have been added on the right. Here the optical data have also been multiplied by ten so it can be seen more easily on this scale. This is a very hot star, so there is relatively little optical radiation. The focus here is on the ultraviolet.

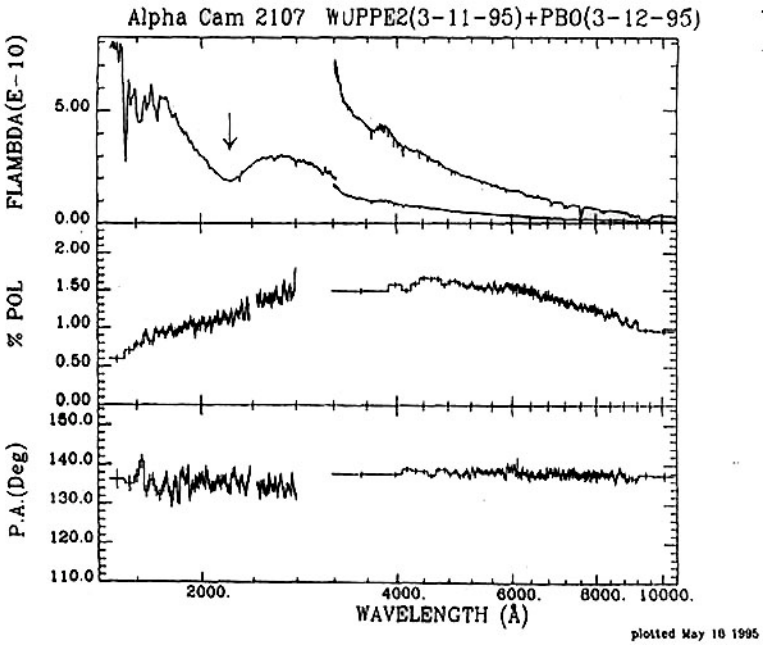


Figure 13. Interstellar polarization for star Alpha CAM in optical and ultraviolet light.

The huge dip in intensity indicated with the arrow is an interstellar absorption feature due to the dust grains in the interstellar medium. It is of great interest because astronomers don't really know what causes it.

The middle graph shows the percent polarization versus wavelength. It's only on the order of one to one and a half percent, which is a very small effect. It therefore requires extremely precise measurements in order to get the results in the first place.

The third piece of information obtained is the position angle of the polarization vector on the sky. In this case it was constant across this entire wavelength region shown, but for some objects it varies with wavelength, providing additional clues about what causes the polarization.

Figure 14 shows the ultraviolet and optical polarization of several stars (Figure 14). These are typical results from WUPPE and their optical counterpart observations to the right. In general, polarization increases toward shorter wavelengths. However, it reaches a peak and then decreases in the ultraviolet region. This was not known before WUPPE's observations were made. The functional behavior of the polarization with wavelength has been described by the empirical "Serkowski curves," but ultimately, measurements such as these will allow a determination of what exactly is going on with the interstellar grains. There is still more work to be done before that is completed.

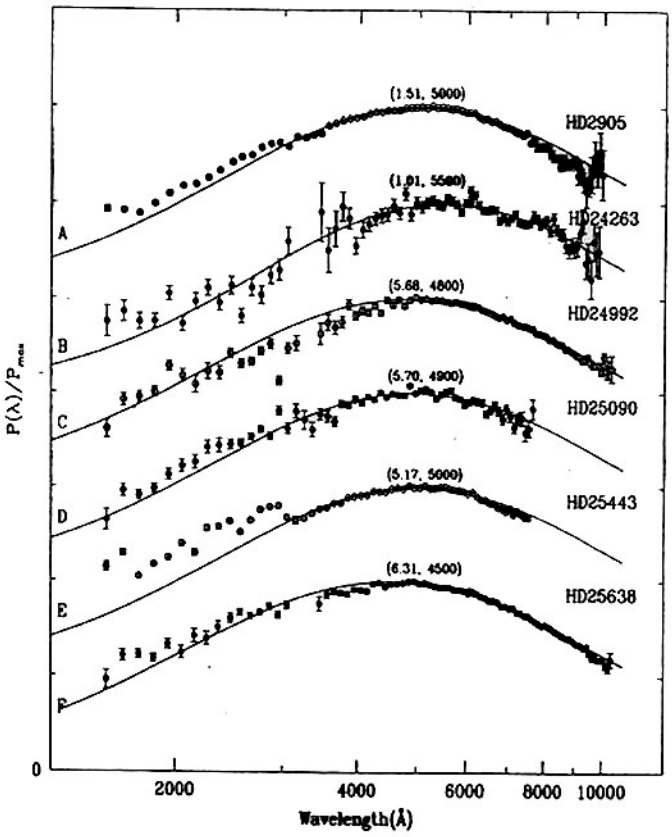


Figure 14. Optical polarization of several stars observed by WUPPE.

The polarization of the Be star, Zeta Tau (Figure 15), provided the WUPPE team with a big surprise. On the right is the optical data on polarization for this emission-line star. Again, it's only on the order of one and a half percent. It dropped in the near ultraviolet, but it was thought that it would recover and increase in the ultraviolet, as shown by the smooth curve. But what WUPPE discovered was that the polarization actually decreases and stays very, very low in ultraviolet. So, a new theory had to be developed to explain these results. Apparently, additional sources of opacity from iron and other elements in the atmosphere of the star cause the surprisingly low polarization in the ultraviolet region.

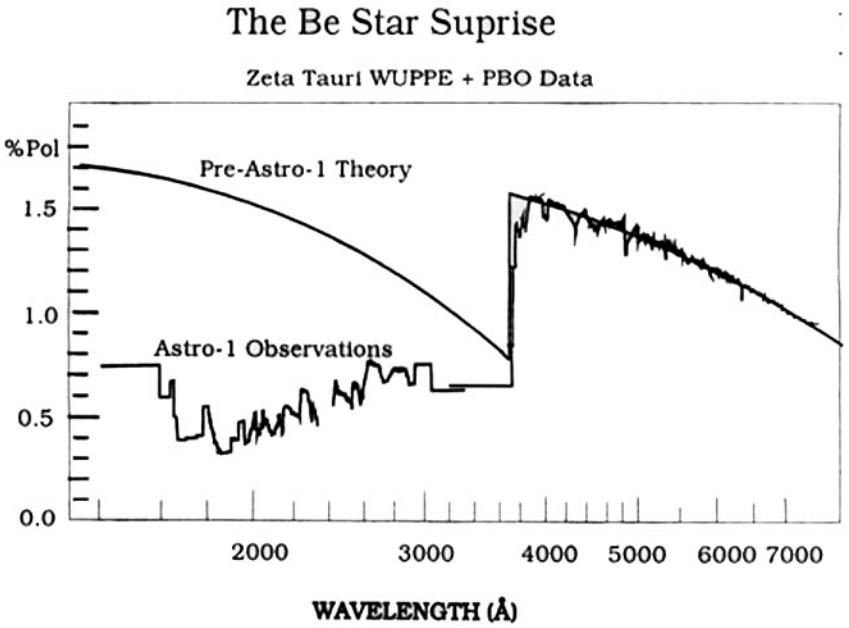


Figure 15. Polarization of Be star Zeta Tau observed by WUPPE.

Here is the UV polarization of Mars measured with WUPPE (Figure 16). The UV is solar radiation scattered from the planet's atmosphere. Most of the light is way out here in the red part of the spectrum. There is very little ultraviolet light by comparison, but it was bright enough to measure in spite of that.

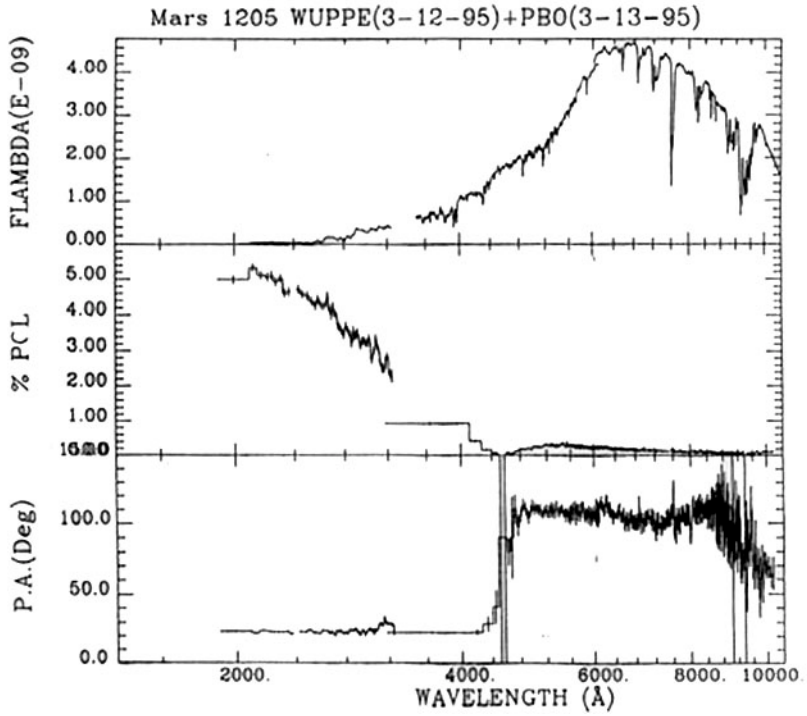


Figure 16. UV polarization of Mars observed by WUPPE.

The polarization, on the other hand, is very low in the optical and then shoots up to 5 percent in the ultraviolet. Also, the position angle changes abruptly from the visible to the ultraviolet, by 90 degrees, in fact. That simply results from the fact that the optical light is being scattered from the planet's surface, while the ultraviolet is being scattered from the atmosphere of Mars. It is this scattering, which increases toward short wavelengths, that produces the change in position angle.

We had a picture of a lot of globular clusters taken with the UIT. Globular clusters contain 100,000 stars or more all swarming around a very small region of space. It looks sort of like an optical picture but in fact, when we take an optical picture, what we see are the cool red giant stars that emit visible light. When we take an ultraviolet picture, those stars disappear completely. What we see instead are the hot stars in that cluster. Of course, there are lots of those as well.

This is an excellent way to discover all the hot stars. These stars are the very old stars that have shed their outer layers. They have gone past the red giant stage, blown off their outer layers, and now we are seeing the interior very hot core of the star, which is collapsing into a white dwarf, which the sun will do about 5 million years from now.

When we compare optical images of a spiral galaxy to UIT images of the same galaxy, what we see is that although this is a spiral galaxy (and with a long exposure of a larger area we would see the spiral arms out further), basically what we see in the optical picture is a fairly smooth distribution of light from the old red giant stars, which are not confined to the spiral arms. When we look in the ultraviolet, what we see very clearly are the spiral arms, where the young stars are created, and those are the hot stars that emit so much ultraviolet in this case.

In the ultraviolet we see rings and the beginning of the spiral arms. There are bright white patches that are not single stars but are clouds of ionized gas. As in the well-known Orion nebula in our own galaxy, there are many stars that are being born out of the interstellar gas clouds, and they create an enormous amount of ultraviolet radiation.

The UIT obtained hundreds of pictures with that kind of data of a variety of different objects during the mission. Some of these images and the associated analysis may be found in the special issue of the Astrophysical Journal Letters that I showed you earlier.

Let me now move on to HUT and give you a sample of the various kinds of science programs we tackled with it, running from the observation of some hot stars, like the PG1159 stars, to a high redshift quasar and intergalactic helium. I will come back and talk about the quasars and the intergalactic medium at length a little later in this presentation.

As you see in the slide (Figure 17) the science program of the PI team for HUT included a large range of topics. Among them were Seyfert galaxies, which have active galactic nuclei that are related to the quasars; elliptical galaxies, the major building blocks of the universe; various kinds of especially interesting stars, including interacting binary stars; the remnants of stars that have exploded as supernovae; and finally a few observations of objects here at home within the solar system.



HUT P.I.
Science Programs for Astro-2

Prog. #	Topic
H 01a	Calibration (includes white dwarf science)
H 01b	PG 1159 and related stars
H 02	High redshift quasars (z > 2) and intergalactic helium
H 03	Low redshift quasars
H 04	Seyfert 1 galaxies
H 05	Seyfert 2 galaxies
H 06	BL Lac objects
H 07a	Elliptical galaxies
H 07b	Subdwarf OB stars
H 08	Probing the Galactic halo
H 09	Cataclysmic variables and related stars
H 10	Supernova remnants
H 12	H_2 in the ISM
H 13	Solar system studies
H 14	OB star spectral atlas

Figure 17. HUT science observations on ASTRO-2.

We also had a guest investigator program. The team leaders and their scientific programs are listed in the slide (Figure 18). The guest investigator program also covered a wide range of topics concerning various interesting types of stars and the interstellar medium, both in our galaxy and in the Magellanic Clouds, our nearest neighbor galaxies. Unfortunately, I don't have time here to show you most of their results.



HUT Guest Investigator
Science Programs for Astro-2

Prog. #	Topic	G.I.
G11*	Symbiotic stars	B. Espey et al.
G12	White dwarfs	D. Finley et al.
G13	Starburst galaxies	C. Leitherer et al.
G14	Interstellar shocks	J. Raymond et al.
G15	03 stars	N. Walborn et al.
G31*	Dust in Magellanic Clouds	G. Clayton
G32*	Wolf-Rayet stars	R. Schulte-Ladbeck et al.

* Joint HUT/WUPPE Program

Figure 18. HUT/ASTRO-2 guest investigators.

As one example, here are the observations of hot white dwarfs obtained for the program G12 (Figure 19). You can see that the spectra extend down to 900 angstroms where the flux drops to zero. That cutoff is due to absorption by the interstellar gas in our own galaxy, the neutral atomic form of hydrogen. If that were not present the stellar spectra would continue to the lower limit for the HUT spectrograph, around 830 Angstroms. The long wavelength limit of our instrument is near 1800 angstroms.

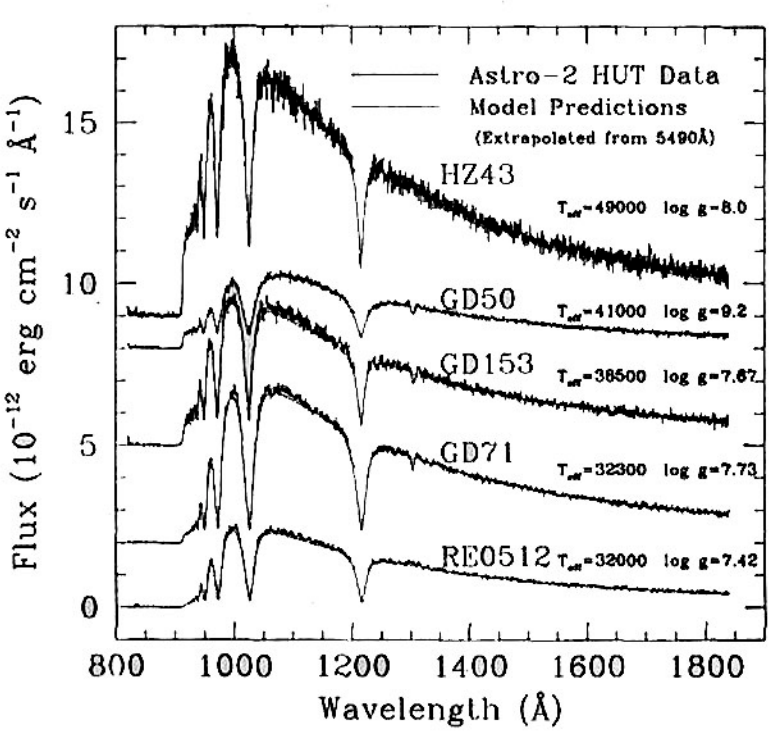


Figure 19. HUT/ASTRO-2 white dwarf observations.

It's clear that for these hot stars most of the radiation is, in fact, found in the far ultraviolet region that has not previously been observable. In fact, the absorption features are nearly all at wavelengths below 1200 Angstroms. That's because these are the absorption lines of the Lyman series in hydrogen. These white dwarfs have pure hydrogen atmospheres. The heavier helium has settled because the gravity is so strong. The helium actually separates out, and we are looking at what appears to be a pure hydrogen atmosphere on the surface of these hot, very, very dense stars. As a result we see only hydrogen absorption lines.

In addition to the data, there is a smooth line going through each of the spectra. That is not a fit to the data. That's the theoretical prediction based on what was known in optical wavelengths and theory of these pure hydrogen atmospheres.

These data verify to a very high degree of accuracy that the theory of the atmospheres of pure hydrogen white dwarfs is extremely good indeed. Therefore, that theory can be used to calibrate other instruments like the Hubble Space Telescope. This is a very important aspect of thse observations, although the stars are very interesting in their own right.

Here is another star that shows us that hot white dwarfs don't all look the same (Figure 20). Again, the flux is rising toward shorter wavelengths in the far ultraviolet where it would not be seen at all with previous instruments. What we found was quite surprising. The wild fluctuations at the short wavelength end of the spectrum are not noise, as one might first have guessed.

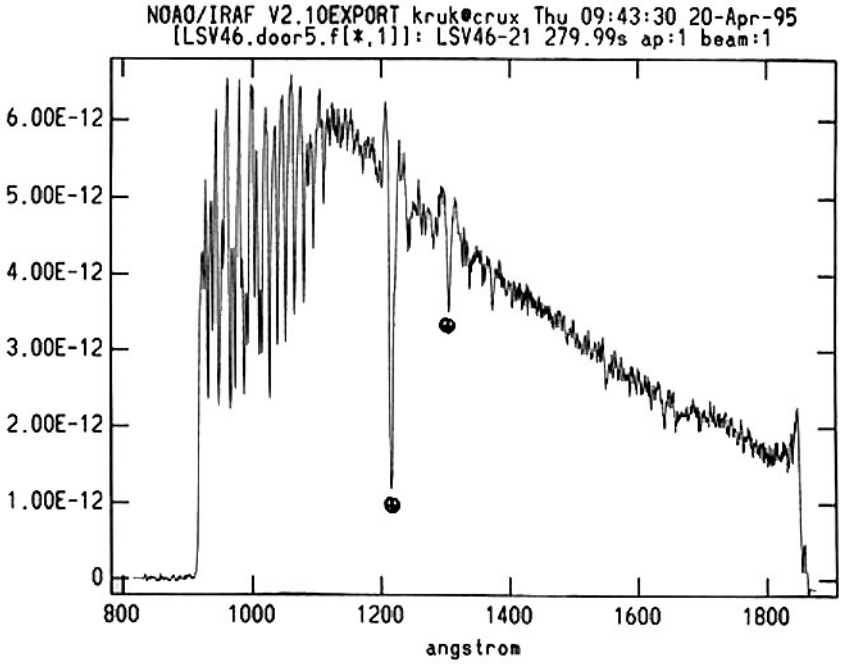


Figure 20. White dwarf observed by HUT.

Here is a blowup of the region (Figure 21). The spectral features are due to absorption by molecular hydrogen in the Lyman and Werner bands. There are due to gas in front of this hot white dwarf. The dwarf

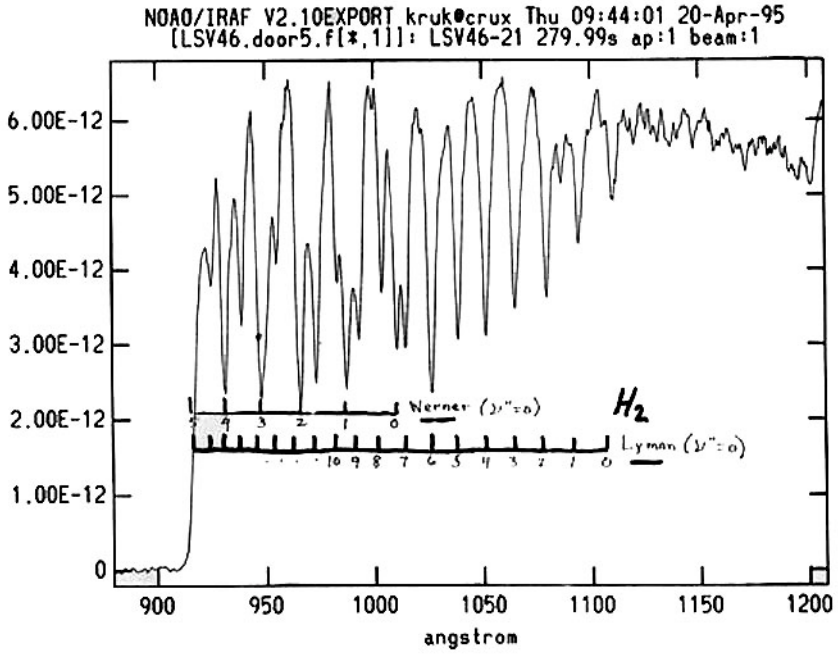


Figure 21. Detail of ultraviolet white dwarf data.

itself is much too hot for molecular hydrogen, but it has a large shell around it. That star has actually expelled the shell which has cooled and has formed lots of molecular hydrogen. We are looking through it in this case, and we have a very sensitive measurement of the amount. At longer wavelengths, molecular hydrogen would not be detected at all. Of course, it's one of the important constituents of matter in the universe.

Turning now to galaxies beyond our own, here is a collection of HUT spectra of elliptical galaxies (Figure 22). Nothing like this data existed before Astro. There was a surprising discovery many years ago that there was a considerable flux of ultraviolet light coming from elliptical galaxies. It was a huge surprise, because elliptical galaxies are billions of years old and they are dominated by old red giants, which emit very little UV radiation.

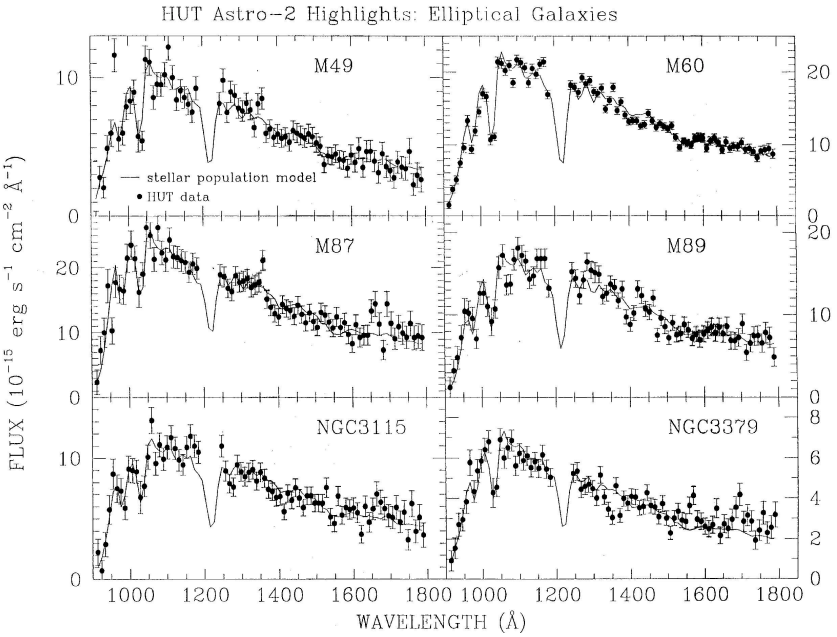


Figure 22. Ultraviolet data from elliptical galaxies.

We now know from these data that the UV comes from highly evolved stars that have blown off their outer layers and are in the process of becoming white dwarfs. The smooth curves through these data are theoretical models for what one would expect to see from a whole population of evolving stars in these galaxies. They provide fairly good fits. So we think we understand now, almost 30 years after its initial discovery, what produces the ultraviolet light from these old stellar populations.

Now I would like to focus in some detail on a very important scientifif result that was obtained with HUT (Figure 23). This was our primary scientific goal, an attempt to detect the primordial intergalactic medium - that is, the stuff that was created in the big bang itself, the matter out of which the galaxies later formed. It's a gas that filled all space quite uniformly in the beginning, although it became clumpy as time went on. It is necessary to look far away to see it. That means we also have to look far back in time, of course.

Astronomers had looked for widely distributed primordial hydrogen for decades without success. So our idea was to look for the helium which is expected to be formed in the big bang. While there was only 10

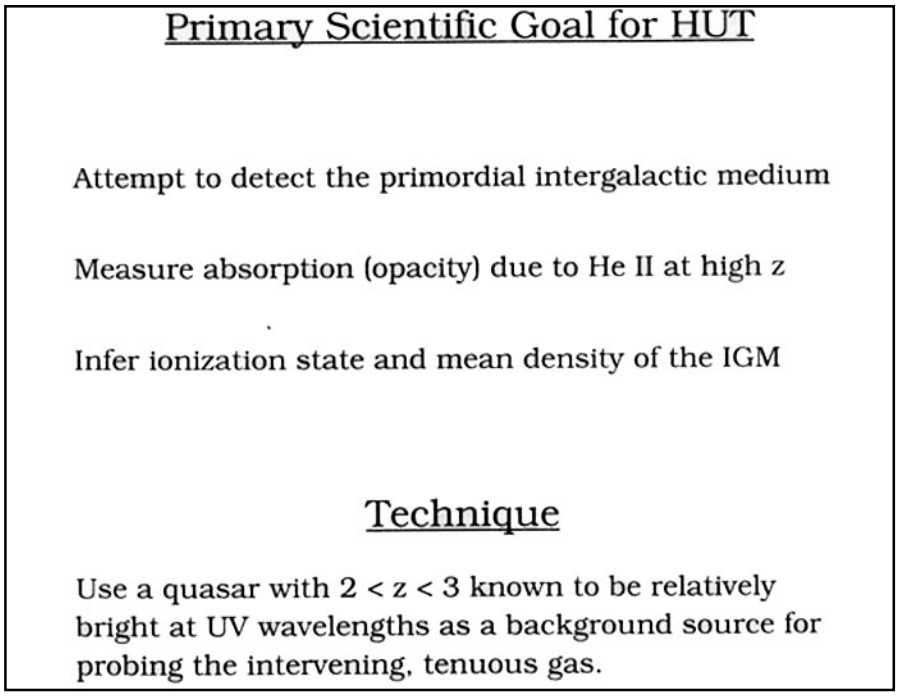


Figure 23. Primary science goal for HUT.

percent as much helium as hydrogen produced by the nuclear reactions that occurred in the first few minutes after the big bang, it seemed likely that a larger fraction fo the helium might be in an ionization state where it could be detected in the far ultraviolet region of the spectrum. The theory is pretty well understood.

If we detected the helium, we hoped to be able to infer the ionization balance and thus the mean density of intergalactic gas. The technique is to look at a quasar far away that is at a redshift from two to three or so. A quasar known to be relatively bright in the ultraviolet was needed so that we would have enough light to use it as a background source for this difficult observation. We would then search for absorption by the intervening gas toward that quasar and try to detect evidence of the primordial intergalactic medium.

To illustrate it, I've got this little cartoon (Figure 24). The big bang is in the upper right corner, and here we are in the lower left corner, representing the present time. So, time has increased from right to left. Look-back time, which is the time into the past, goes to the right. The redshift corresponds to that, telling us how far away the objects are and how far back in time we are looking. The big bang occurred about 14 billion years ago.

What we see near us at redshifts much less than one are these big galaxies. As we go further away, we see the quasars, the black dots, and there are more and more of them as we go back in time. Also we find thin clouds of gas, which are intergalactic clouds. These are detected through their absorption of the light coming from the quasars.

The large dot represents the quasar we chose. It's at a redshift of almost three and it's very bright in the ultraviolet. We knew that much. We were looking along that line of sight to see if we could find any of the gas that was created earlier and was still left over at this point, a few billion years after. perhaps just a big

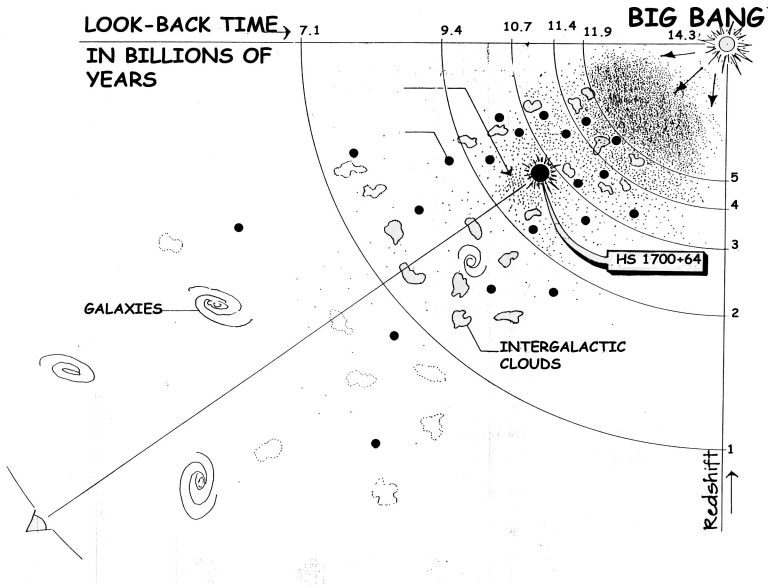


Figure 24. Illustration of the technique used to search for primordial intergalactic media.

Here is another diagram explaining how we do that (Figure 25). The top part of the diagram illustrates a line of sight to the quasar that passes through intergalactic clouds as well as through more diffuse matter between the clouds. In the lower part of the figure is a schematic spectrum, showing an emission line (H Lyman alpha) corresponding to the quasar itself, and a continuum at all wavelengths due also to emission by the quasar. Superimposed on this continuum are the effects of absorption in the intergalactic medium. There is an overall depression, which is strongest at the higher wavelengths and becomes weaker at shorter wavelengths. This arises from the diffuse gas, whose density is greater at longer wavelengths, which correspond to larger redshifts and hence greater look-back times.

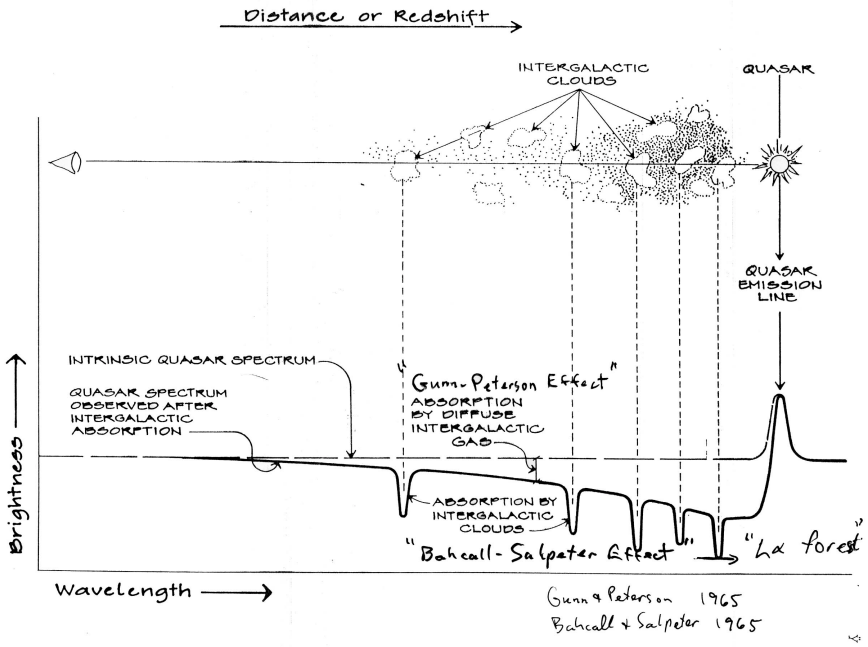


Figure 25. Illustration of the redshift effect in quasars.

We also see discrete dips corresponding to each of the clouds through which our line of sight passes. Those that are closest to us have smaller redshifts and therefore appear at shorter wavelengths.

Now Figure 25 refers to absorption by hydrogen atoms. Extensive work over the past twenty-five years revealed only the discrete lines corresponding to the intergalactic clouds, with no evidence for the diffuse matter between the clouds. The conclusion that was drawn is that the intergalactic gas must be very highly ionized. Hydrogen ions, stripped of their single electron, will not produce the absorption for which astronomers were searching.

Here things get a little more complicated (Figure 26). Figure 26 adds the spectral features of singly ionized helium, known to astronomers as He II. The resonance lines of this ion appear in the far-ultraviolet part of the spectrum, at 304 angstroms and below. In quasars where the hydrogen lines are redshifted into the visible part of the spectrum, the helium lines are redshifted up to the ultraviolet band that is observable with HUT.

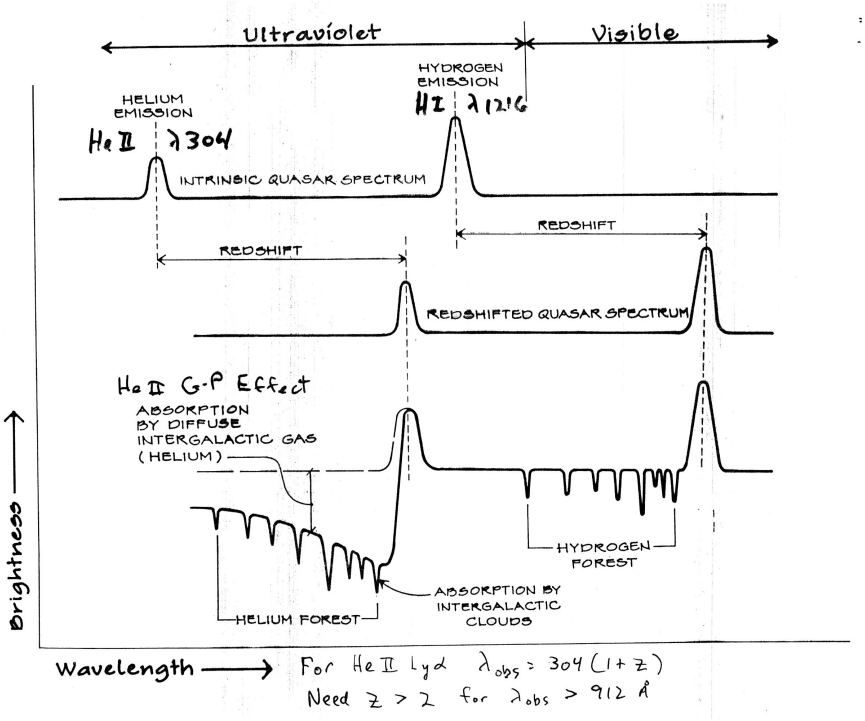


Figure 26. Hydrogen and helium emission lines for ultraviolet and visible light.

With HUT, then, we expected to see a helium emission line from the quasar, and absorption from the helium ions in the same clouds seen in the hydrogen line, and perhaps also a further continuous dip due to diffusely distributed helium in the intergalactic medium. The helium absorption signature was expected to be stronger than that due to hydrogen, because it appeared likely that there were far more helium ions that neutral hydrogen atoms in intergalactic space. This is true despite the fact that, overall, the total amount of hydrogen is about ten times the amount of helium.

Figure 27 shows the result of our experiment (Figure 27). It is the spectrum in the far ultraviolet of the quasar HS 1700+64 (the heavy line). The peak labeled He II is the emission line from the quasar itself, but

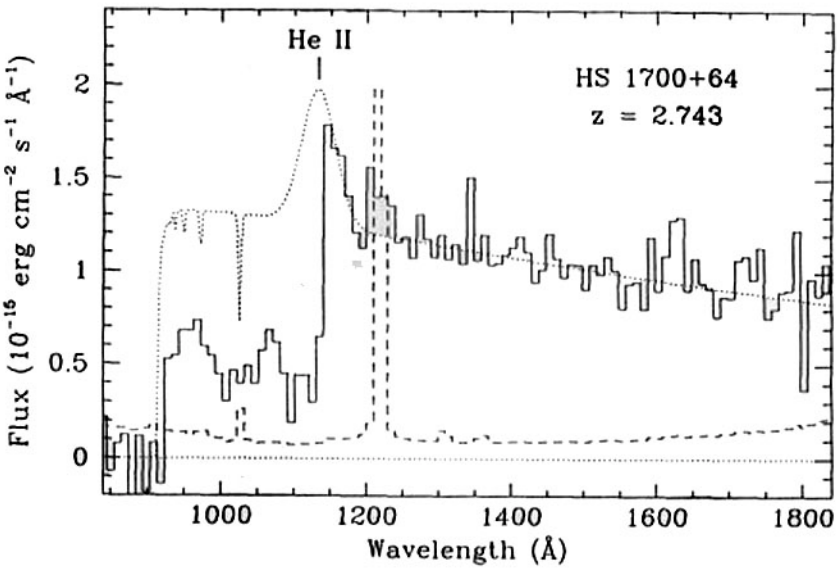


Figure 27. Far ultraviolet spectrum for quasar HS 1700 plus 64.

from there to shorter wavelengths the flux is strongly depressed compared to the light line, which indicates the expected flux from the quasar if no intergalactic helium were present. The sharp drop at the He II wavelength clearly indicates the detection of intergalactic helium.

The level of the flux in the broad absorption trough allows us to estimate the actual density of helium ions at a redshift corresponding to a look-back time of about 10 billion years. Then with the help of calculations of the expected ionization balance in the gas it is possible to get an estimate of the total density of the intergalactic medium.

Figure 28 is the same data at higher resolution, showing just the short wavelength portion of Figure 27 (Figure 28). We believe we have actually detected some of the clouds as well, the strong dips where the flux goes down almost to zero. In between those clouds there is a large depression of the flux overall, and it turns out that this strong depression can't be explained by the clouds that are known to be in the path of that quasar.

Subsequently, theorists were able to compute what we might see, and indeed, they computed exactly what we did see. The diffuse hydrogen turned out to be undetectable because of its very high degree of ionization, while the less abundant element helium revealed the existence of a diffuse intergalactic medium because helium is not quite as highly ionized as hydrogen.

The conclusions for this work are listed in Figure 29 (Figure 29). First of all, we definitely detected this intergalactic helium, the primordial helium, which is a demonstration that the big bang theory is basically right, since it predicts the existence of primordial helium.

We measured the opacity at a particular redshift, corresponding to a look-back time of 10 billion years.

The measured opacity implies that the gas is very highly ionized, i.e. it is mostly in the form of H II and He III.

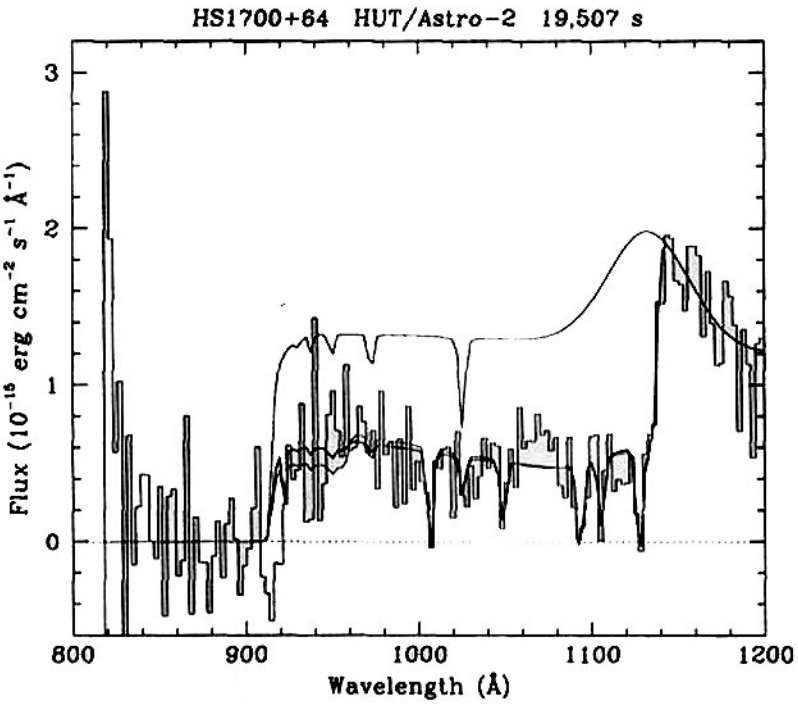


Figure 28. Increased resolution ultraviolet data for quasar HS 1700 plus 64.

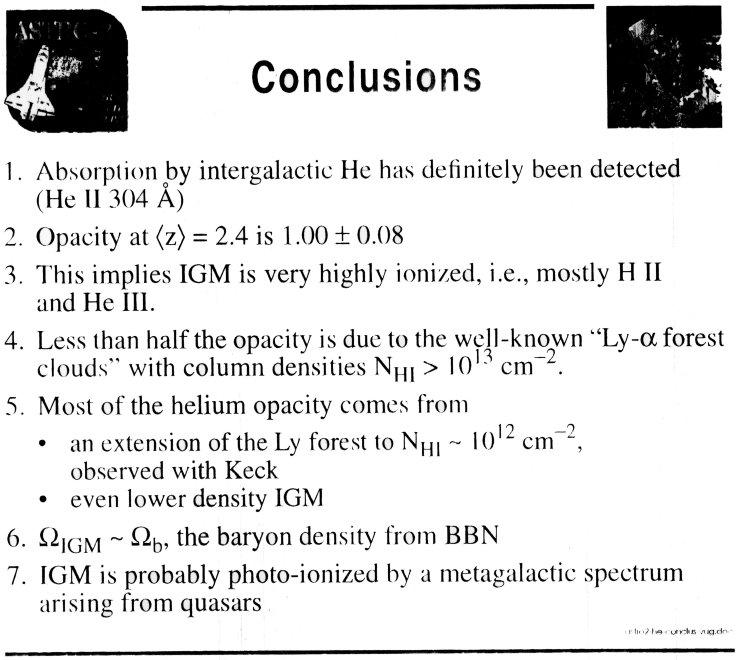


Figure 29. Conclusions from ASTRO-1 and ASTRO-2.

We also found that this opacity is not explained by just the clouds themselves, but it requires additional diffuse material. Most of the helium opacity effect comes from very low density gas. It is undetectable even with the Keck telescope, the biggest and best optical telescope on the planet.

When we interpret this in terms of the theory, we find that that the parameter omega, which is the average density measured in terms of the critical density that would eventually cause the universe to stop expanding, is approximately equal to the value that is predicted to exist in the form of baryons, that is, heavy particles like protons and neutrons, including ionized helium, from the big bang theory.

In other words, out at that time, 10 billion years ago, almost all matter was still spread through intergalactic space. Most of it had not yet condensed into galaxies. Obviously, it condensed into some quasars because we see them out there, and there are some galaxies, but most of the matter was still spread widely through space. The amount of matter we find is exactly what we think should be there based on our theory of the big bang.

Furthermore, the photo-ionization that appears to be arising from the quasars themselves produces a lot of ultraviolet and x-radiation, which is sufficient to keep that gas extremely highly ionized, making it hard for us to see. It was, however, not impossible, thanks to the Astro observatory on Spacelab.

That’s the end of my presentation. Thank you.

Question and Answer

QUESTION: I was wondering if any of your experiments or any of your data showed any shifts from visible to ultraviolet, some blueshift data.

DR. DAVIDSEN: Not of any great significance. One of the things we set out wondering about when we started back in the 1970s was whether the material shot out of the quasars toward us. That was the debate back then. That has been resolved in favor of the intervening galactic clouds. We could have detected blue-shifted things, but we didn't, except for very small shifts. When you look at a star that is exploding, for example, you can see a blue-shift at a small level with the material coming toward us from that star.

QUESTION: But nothing that was all the way from visible to ultraviolet?

DR. DAVIDSEN: No.

Spacelab Life Sciences Research Panel
Dr. Frank Sulzman, Panel Moderator

My name is Frank Sulzman. I'm the lead scientist in the Life Science Division at NASA Headquarters. I had the pleasure of both being an investigator on Spacelab and also a program scientist for one of the Spacelab missions. I am very pleased with this event. I think you will enjoy what we have to tell you about some of the life sciences research that was conducted on Spacelab missions.

Dr. Mary Ann Frey is joining us up front. Mary Ann was the program scientist for Neurolab, the last Spacelab mission. She will also be saying a few words and introducing one of the speakers.

I think we have a very interesting session. You will be pleased both by the quality of what we've got and also the comprehensive nature.

The theme of this comprehensive nature is going to be led by our first speaker, Dr. Larry Young. I've had the good fortune of knowing Larry from the beginning of the Spacelab program when he and I were both investigators on Spacelab-1, which flew in 1983.

Larry is the Apollo professor of astronautics at MIT. He's the director of the National Space Biomedical Research Institute. He was a PI or co-investigator on all of the Spacelab missions. He has been heavily involved with NASA since the 1970s. Larry was also an alternate payload specialist on SLS-1. So he has seen missions from very different perspectives. He's the director of the Massachusetts Space Grant Consortium, and he feels like he is home here because he's a member of the National Academy of Engineering and a member of the Institute of Medicine. He's also a member of the International Academy of Astronautics.

We are very pleased to have Larry speak. Larry will be providing us with an overview of the Life Sciences Spacelabs.

Spacelab Contributions to Space Life Sciences*

Laurence R. Young, ScD[1] and Rhea Seddon, MD[2]
[1]Massachusetts Institute of Technology, Cambridge, MA
[2]Vanderbilt University, Nashville, TN

Abstract

Gravity is perhaps the most important environmental factor affecting the development of life on Earth, yet it has been difficult to study its effects because it can't easily be "turned off." From the outset of the space program scientists have explored various aspects of gravitational biology as well as the role of gravity and its absence in support of humans in space. Beginning with Skylab, and continuing much more extensively with Spacelab, the answers are beginning to accumulate and to provide some dramatic surprises.

The National Aeronautics and Space Administration (NASA) developed a life sciences research program for the Shuttle/Spacelab focused on discovering the mechanisms involved with changes during and following weightlessness. This paper discusses various components of this program, including research objectives, hardware, ground-based research, and science results. The focus is on achievements in life sciences research aboard Spacelab during the past ten years.

Introduction

Prior to the first flight of man in space, it was considered likely that he would have difficulty surviving even brief orbital exposure. The most evident concern was with the cardiovascular system and the real possibility that a shift of blood and other fluids from the legs to the chest and head would overload the heart, which would not be able to clear all of the returning blood from the veins. Other major initial concerns related to muscle and bone loss, inability to eat or sleep, and motion sickness. Fortunately, none of these problems were too severe at first, and NASA, along with the Soviet Union space program, proceeded to go from short orbital flights to preparation for the journey to the moon.

Project Mercury marked the beginning of the U.S. space program and the beginning of space physiology research. The ultimate goal of this project, as well as subsequent manned missions, was to send astronauts into space and return them safely.

With this goal in mind, NASA has placed a strong emphasis on the study of human physiology in space. Knowledge in this area has expanded steadily from the early Mercury, Gemini, and Apollo flights and took a large step forward with the flight of Skylabs 2, 3, and 4. Skylab was the first opportunity for scientists to study habitability and physiologic adaptation in space over an extended period of time. Studies conducted on Skylab allowed the collection of data on nine humans who lived in space for either 28, 59, or 84 days.

Investigations covered the areas of biochemistry, hematology, cytology, neurophysiology, and musculoskeletal, cardiovascular, and metabolic functions. Skylab data indicated the following adaptive processes occurred in weightlessness: space motion sickness, loss of muscle strength, loss of lean body mass, loss of

*Originally published as AIAA 94-4649 Part II.

plasma volume, loss of red cell mass, changes in cardiovascular function, changes in lymphocyte responsiveness, and changes in metabolic functions. It demonstrated that the various physiological systems adapted to weightlessness at different rates, and led to the early tests of a treadmill exerciser to attempt to overcome some of the cardiovascular deconditioning problems. Among the surprises was the total absence of motion sickness symptoms during a "Coriolis test" of head pitching while yawing, carried out first during the fifth day in flight, and a carry-over of this apparent immunity to post flight. The important postflight studies also revealed the extent of deconditioning and some of the difficulties in readapting to Earth's gravity, including postural instability, tendency toward fainting, and bone loss.

While a great deal of information was gathered on these changes and new insights were gained about their time course, experimental results led to the formulation of questions regarding the mechanisms involved in human adaptation to space flight.

The Shuttle/Spacelab offered the capability for extending research in the unique environment of space flight, using a laboratory environment and tools similar to what is found in a good ground laboratory. The Spacelab facility provides a shirt-sleeve atmosphere for the conduct of experiments. But although the Shuttle/Spacelab offers greater resources than Skylab, research conditions are still not ideal. Investigators often face limited flight opportunities, long delays between proposal and flight, limited flexibility in experiment protocol adjustment, inadequate crew time, competition for video, power and other mission resources, and small subject populations. Also, the remoteness of the Shuttle facility can make it difficult to recover from hardware malfunctions. Finally, the extreme concern about crew safety puts even greater constraints on testing than when on the ground, and makes it impossible to conduct exploratory research that has not previously been well rehearsed and documented. Despite the operational constraints and resource limitations, the introduction of the Shuttle and the development of the Spacelab has led to ten years of great achievements in space life sciences. Experimental results have provided supporting evidence to some theories, provided new insight to others, and have surprised scientists with data that refute some long-held ideas of biology and physiology in space and on Earth.

Objectives

The NASA Life Sciences Program has four goals as stated in the 1978 Announcement of Opportunity (AO) for flight experiments:

1) to ensure human health, safety, well-being and effective performance in space flight;

2) to use the space environment to further knowledge in Earth medicine and biology;

3) to use space technology and the space environment for application to terrestrial medicine and biological problems; and

4) to understand the origin and distribution of life in the universe.

The AO suggested the following topics for research which summarizes the science objectives of space life sciences research on humans in the past decade:

Cardiovascular: To study the causative mechanisms and develop means to prevent or reduce orthostatic intolerance manifested in flight and postflight.

Musculoskeletal: To identify the primary mechanisms of mass and strength loss in anti-gravity muscle groups (and mechanisms causing the decrease in bone density).

Neuroscience: To investigate the causative mechanisms and develop means to prevent or reduce disorientation and nausea which sometimes occurs during the first few days of exposure to weightlessness (and upon return to Earth).

Regulatory Physiology: To identify the physiologic mechanisms and consequences of fluid and electrolyte shifts (and loss of red blood cell mass) which accompany the onset of weightlessness.

Behavior and Performance: To investigate the impact of exposure to weightlessness, and concomitant physiological changes, on human behavior and performance.

Components of Human Space Life Sciences Research

Spacelab Missions

As stated previously, NASA has placed a strong emphasis on life sciences research in space. Table 1 lists those Spacelab missions that involved life sciences research over the past decade. The experiments conducted on these missions covered several disciplines: regulatory physiology, cardiovascular/cardiopulmonary, musculoskeletal, neuroscience, behavior and performance, and environmental health. While there has been extensive research using animals, this paper will focus on highlights of human research in the major disciplines.

Table 1. Spacelab missions involving life science.

Research Mission	**Date**
Spacelab 1 (SL-1)	November 1983
Spacelab 3 (SL-3)	April 1985
Spacelab 2 (SL-2)	July 1985
Deutsche Spacelab 1 (D-1)	October 1985
Spacelab Life Sciences 1 (SLS-1)	June 1991
International Microgravity Laboratory 1 (IML-1)	January 1992
US Microgravity Laboratory 1 (USML-1)	June 1992
Japanese Spacelab (SL-J)	September 1992
Deutsche Spacelab 2 (D-2)	April 1993
Spacelab Life Sciences 2 (SLS-2)	October 1993

Ground-based Research

There are two categories of ground-based research. Supporting studies aid in the development and validation of the experiment protocol. For example, several head-down tilt studies have been tested for application as a ground-based analog of space flight. The second category is pre and postflight data collection on astronauts. The purpose of preflight data collection sets is to establish a baseline for comparison to in-flight and postflight data. Missions that include life sciences experiments in flight also involve physiologic data collected at various intervals preflight. Depending on the investigation, data collection sets can be scheduled at any time within one year of launch.

The purpose of postflight data collection is to measure the immediate response to return to 1-gravity (1-g) and the longer term readaptation to 1-g. Seven days of postflight data collection with follow-ups at various intervals for up to three months is typical for life sciences missions.

For plants and animals the usual practice is to carry out extensive ground-based studies to work out protocols and to establish a 1-g baseline. In many cases small centrifuges can be used on the ground to explore the regions above one gravity.

Both human and animal experiments make extensive use of short period exposure to weightlessness in NASA's KC-135 zero-g airplane, which is capable of making repeated parabolic flights of 20-25 sec of weightlessness, followed by a slightly longer pullout period of approximately 1.8 g's.

Hardware

One important element in the success of human life sciences research has been the development of reliable, versatile hardware that meets space flight standards. The NASA Life Sciences Division has developed hardware that can be grouped into four categories: Life Sciences Laboratory Equipment, or LSLE hardware; Principal Investigator (PI) Provided Hardware, Experiment Unique Equipment, or EUE hardware; and Extended Duration Orbiter Medical Program, or EDOMP hardware.

LSLE is generic laboratory hardware developed by the NASA Life Sciences Division and is intended for use on multiple space flight missions. LSLE is comprised of scientific equipment, supplies, etc., which are used wherever possible to reduce new equipment development and program costs. Examples of LSLE include animal habitats, centrifuges, experiment computers, a bicycle ergometer, a gas analyzer/mass spectrometer, a body mass measurement device, a urine monitoring system, and an blood collection system. A "glove box," capable of isolating a sample or toxic chemicals from the cabin air during certain activities, including those which expose animals or their waste, is essential to successful in-flight life biology.

The second category is hardware developed by a Principal Investigator team for a specific flight experiment and is called PI-provided hardware. This category consists of unique hardware required to implement a specific experiment and is typically approved at the NASA program level at the time of experiment selection. Examples of PI provided hardware include the Neck Chamber System developed to support Dr. Duane Eckberg's baroreflex investigation flown on the SLS-1 and D-2 missions and Dr. Gunnar Blomqvist's system for indwelling catheter measurement of central venous pressure flown on the SLS-1 and SLS-2 missions. At MIT, we developed specialized equipment, such as the "rotating dome" and accessory hard-

ware for measuring spatial orientation and head and eye movements associated with disorientation in weightlessness (Figure 1). All PI-provided hardware is owned by NASA and is available for future missions.



Figure 1. The "rotating dome" experiment tests the way subjects react to a rotating visual field in space, where the usual inertial cues no longer furnish a vertical reference. (The subject is author MRS). (STS058-205-028)

The third category, which can be developed by either NASA or the PI team, is known as Experiment Unique, or EUE hardware. EUE is typically small hardware items developed to facilitate the implementation of a specific experiment and typically only flies once. EUE hardware include items such as experiment unique electrodes or cables connected to existing hardware, special fixative or specimen bags, isotope syringes, and contact lenses used in vestibular experiments.

The fourth group of life sciences hardware flown on Spacelab missions is that flown as part of the Extended Duration Orbiter Medical Program, or EDOMP hardware. This program is intended to explore operationally important aspects of qualifying astronauts for orbital flights of successively longer durations, leading up to the 90 day or 180 day increments foreseen for the Space Station. Examples of EDOMP hardware include the American flight echocardiograph, the cycle ergometer, the automatic blood pressure monitor, and the Lower Body Negative Pressure (LBNP) Device.

Science Results

The human body displays extraordinary adaptive capabilities. It constantly works to maintain homeostasis under changing environmental conditions. The weightlessness of space flight is one of the most unusual environments that humans can experience. Data from Skylab and subsequent missions demonstrated that the astronauts' bodies use unique mechanisms to maintain homeostasis. In most cases, the knowledge gained from the space experiments is applicable to the understanding of gravitational effects on Earth and the nature of a variety of diseases.

In space, the fluids normally pooled in the lower part of the body due to gravity will become evenly distributed throughout the body. Consequently, one of the first reactions to weightlessness is a shift in fluid

toward the head and upper thorax, which creates a sensation of hypervolemia or excess blood volume in the body. SL-1 investigators collected peripheral venous pressure data and hernatocrit values pre and post-flight. They concluded that the fluid shift probably occurs within three to six hours of exposure to weightlessness. Later studies indicated that the shift may begin as early as during the period on the launch pad, while the astronaut reclines with his legs higher than his head. The body reacts appropriately to get rid of this excess fluid by several mechanisms. The levels of fluid balance hormones such as aldosterone, antidiuretic hormone (ADH), and atrial natriuretic factor (ANF), as well as fluid electrolyte levels, were measured from blood and urine samples (Leach, 1992). The hormones work in conjunction to control the amount of water excreted by the kidney either by changing the permeability of the nephron tubules to water (ADH), by changing the sodium transport system in the nephron (aldosterone), or by controlling the amount of sodium excreted by the kidneys (ANF). In the subjects tested on SLS-1 and SLS-2, it was found that aldosterone levels decreased in flight, ANF decreased slightly. ADH levels were variable in some flights but showed an early suppression in SLS-2. Serum osmolality showed a tendency to increase with serum potassium being elevated and serum sodium being reduced. The kidneys respond by excreting more water with a resultant decrease of plasma volume. However, the expected early evidence of diuresis was not found (Leach, 1994).

A less obvious physiological change related to the fluid shift is the reduction in red blood (RBC) mass. It has been proposed that the decrease in plasma volume results in a higher concentration of red blood cells. The body perceives an excess number of red blood cells and decreases production, by means of mechanisms which are still under study. Astronaut blood samples yielded several key hematologic parameters, including cell counts, erythropoietin (EPO) levels, iron kinetics values, and plasma volume. Plasma volume decreased as expected. EPO levels decreased, which meant RBC production was not being stimulated. RBC survival was unchanged, indicating RBCs were not being destroyed in space, but that all of the RBC loss was attributable to the reduction in production of new cells to replace the normal death of existing RBCs.

Ferritin (storage form of iron) levels increased and serum transferrin (transport form of iron) levels were unchanged but iron incorporation was decreased which initially appeared conflicting. Where was the extra iron going? The investigator has proposed a mechanism based on the concept of “apoptosis” or programmed cell death. It is believed that red blood cells are still being produced in the bone marrow. Since these new RBCs would be excessive to the needs at the time, they are somehow not being released as mature blood cells but rather are self-destructing (Alfrey et al., 1993a).

Closely related experiments using rats in space, with ground controls, were useful in working out some of the underlying regulatory mechanisms. Using radioactive tracers, it was determined that the production of RBCs in the rats, as in humans, was turned off in space, but that existing RBCs survived normally. Unlike humans, however, the space rats show no decrease in plasma volume (Alfrey et al., 1993b). Detailed investigation of the factors involved in the reduced production of RBCs in space has yielded an important new finding. The cells which are involved in bone marrow production or RBCs are interfered with by a reduction in the level of specific early progenitor cells (blood forming units BFU-E, and colony forming units CFU-E) (Zuhair et al., 1994).

The cardiovascular system is closely tied to the fluid/electrolyte balance system and is also quick to respond to the loss of the force of gravity. The demands on the cardiovascular system are reduced in weight-

lessness because it no longer needs to overcome the hydrostatic pressure between heart and head. However, the reduced blood volume places other demands on the system. The headward fluid shift changes several cardiovascular parameters, including heart rate, cardiac output, cardiac dimensions, and central venous pressure. Data from Skylab demonstrated that there is a slightly higher heart rate and an increase in systolic blood pressure (the period of contraction) and a decrease in diastolic blood pressure (the period of relaxation).

Data from several complementary experiments on SLS-1 and SLS-2 showed that stroke volume (the volume of blood ejected from the left ventricle at each beat) and cardiac output (the volume of blood ejected from the heart each minute) increased in flight. Both echocardiograph measurements and indirect measurements using breath-by-breath gas analysis showed that the increased stroke volume, without change in heart rate in microgravity, accounted for increased cardiac output. Since blood pressure did not change, the peripheral resistance in the circulation was found to have dropped in weightlessness (Blomqvist, 1994, Prisk et al., 1993, Fahri, 1994). The results of venous compliance and blood flow measurements in the leg showed an increase of compliance that lasted up to a week following the return.

A major concern of the cardiovascular adaptation process is postflight orthostatic intolerance. The proposed theory held that the decrease in blood volume and pooling of blood in the legs were major contributing factors to the postflight orthostatic intolerance characteristic of readaptation to Earth's gravity. Investigators had believed that blood pooling in the legs postflight was a contributing factor to an exaggerated drop in stroke volume. SLS-1, SLS-2 and D-2 subjects performed a stand test upon landing and 9/14 could not complete the 10 minute test. A body impedance measurement device was used and indicated that the postflight drop in stroke volume may have been due to blood pooling in the splanchnic venous system instead of in the legs as previously thought. The results are of interest to those studying related cardiovascular inability to regulate pressure during standing in certain patients.

The most surprising finding has been the changes seen in central venous pressure (CVP), which was expected to increase with the extra fluid in the upper body. D-1 investigators measured peripheral venous pressure in an antecubital vein and found that it did not increase (Kirsch, 1986). A theory was proposed that the crew member's supine position while on the launch pad allows the process of adaptation and headward blood shift to begin. Investigators on SLS-1 and SLS-2 observed CVP measurements directly with a catheter inserted near the heart to eliminate the pressure drop between the heart and the arm even in weightlessness. Rather than seeing the expected venous pressure increase on entry into weightlessness, they started to see an increase while the crewmember was still on the launch pad supporting the previous theory, followed by a surprising CVP drop once the subject entered weightlessness (Buckey et al., 1993). D-2 investigators using a different type of catheter (transducer-tipped versus fluid-tipped), also measured a drop in CVP. An entirely new view of gravity effects on regulation of blood pressure and flow needed to be developed and this is a current subject of high interest.

Another theory proposed to explain postflight orthostatic intolerance is impairment of the baroreflex function, which normally regulates blood pressure. Data from SLS-1 and D-2 crew members have been collected. Carotid baroreceptors were stimulated by various pressures (ranging from -65 mm Hg to 40 mm Hg) and the measured heart rate increases (due to perceived blood pressure drops) declined steadily in flight, indicating that the regulatory system, as well as the blood volume loss and mechanical changes, is responsible for the cardiovascular deconditioning (Eckberg and Fritsch, 1993). Baroreflex responsiveness

was recovered within days of landing. These data suggest that the ability of the baroreceptors to function properly degraded over time and thus led to the conclusion that baroreceptor function is related to the loss of orthostatic tolerance.

Postflight orthostatic intolerance is a great operational concern due to the upright posture of astronauts on reentry, particularly the pilot involved in landing the Shuttle. One countermeasure developed by a NASA investigator was tested on recent Spacelab missions. The protocol involves applying lower body negative pressure (LBNP) while salt and fluid are ingested. Heart rate and blood pressure are measured during the protocol. Combined results from several missions indicated that the loss of orthostatic tolerance may occur earlier in flight than indicated by Skylab data. It is possible that a "deep soak" of exposure to extended LBNP shortly before reentry may obviate the usual orthostatic symptoms.

Related to the cardiovascular system is the pulmonary system, but it has not been studied quite as extensively. One experiment conducted on Skylab demonstrated changes in vital capacity in several crew members. It was determined that the changes were caused partly by the atmosphere in the Skylab, but it could not be determined at the time whether the other factors were the direct effect of weightlessness or indirect effects of the fluid shift. An investigator team designed a protocol to characterize lung function in space and increase the knowledge in this area (Figure 2). Normal lungs function under the influence of gradients of gases and blood flow caused by gravity. Inequality of ventilation and perfusion are characteristic of the human lung on Earth. SLS-1/2 data demonstrated that the ventilation/perfusion ratio did indeed tend toward becoming more uniform along the lung in flight compared with upright 1-g measurements. Unexpectedly, however, spatial variations evidenced by the cardiogenic oscillations in gas mixtures are still present to some degree, and the source of the residual non-gravity related spatial differences in this ratio is a focus of current research (Guy et al., 1994, Prisk et al., 1994).

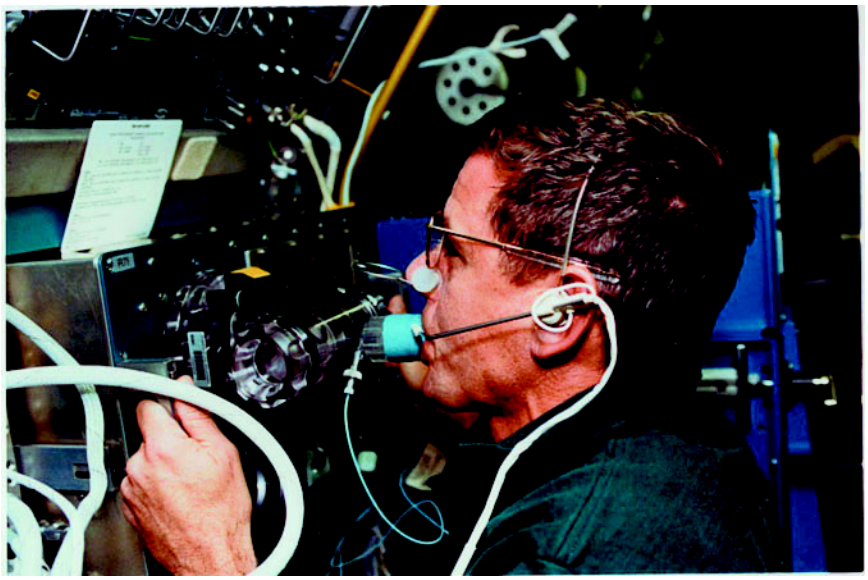


Figure 2. Cardiopulmonary function in space is measured with a gas analysis mass spectrometer, which samples gas exhaled during each breath to determine cardiac output and the distribution of blood and gas in the lung. (STS058-204-024)

The musculoskeletal system has also been examined since Skylab missions. Without the need to constantly support the body weight, the slow fiber 'anti-gravity muscles' and their associated long bones might be expected to deteriorate. Mineral and nitrogen metabolic studies were conducted on all three Skylab missions. Crew members, kept on a strict, monitored diet, showed an increased excretion of calcium, nitrogen (N), and other minerals resulting in a measurable loss of bone and muscle mass. It was concluded that unless countermeasures were developed, musculoskeletal function could be impaired during long duration space flights. A negative N balance could indicate a decrease in protein synthesis or an increase in protein breakdown or both. There are three mechanisms that could be occurring to cause the negative balance. These are the stress response (increase in protein synthesis and breakdown), a bed-rest response (increased breakdown only), or an energy deficiency (a decrease in protein synthesis). An investigation on SLS-1 and SLS-2 examined the loss of lean body mass and decreased muscle strength by measuring the rate of protein synthesis, protein breakdown and the N balance. Data from these missions suggest that the space flight response is similar to the stress response in which there is an increased rate of protein synthesis and breakdown, with a greater rate of breakdown. The muscles show transient damage both on entry into weightlessness and again during re-entry, as indicated by elevated levels of urine Interleukin-6, but it is assumed that the muscle damage is repaired during a two week space flight (Stein et al, 1993). Thus it is consistent with the results of SLS-2 rat muscle dissection, showing the increased susceptibility of rat weight bearing muscles to tearing when tested shortly after landing, but not observed in the animals which were dissected on Flight Day 13 (Riley, 1994). Further biochemical analyses of rat muscle postflight samples contributed to a picture of selective interference of space flight primarily with the slow muscle fibers, those normally used to support weight (Baldwin, K.M., et al., 1993, Haddad et al., 1993, Hoh, 1994). Astronaut muscle strength and stamina showed interesting parallel changes postflight (Young et al., 1993).

Bones are dynamically changing structures, which normally go through a continuous process of building new material from calcium and returning calcium to the blood stream through breakdown of bone. It has been known that gravity and bone loading are important for the maintenance of bone density and strength, and possibly for calcium regulation. A loss of calcium is related to the decrease in bone density that has been consistently measured in astronauts following space flight. To understand the mechanism involved, investigators measured parathyroid hormone (PTH) and calcitonin, hormones involved in bone synthesis and breakdown (Arnaud and Cann, 1994). Calcitonin is released in response to excess ionized calcium in the blood and stimulates deposition of calcium in the bones. PTH is released in response to inadequate amounts of ionized calcium in the blood and resorbs calcium out of the bones. On both SLS-1 and SLS-2, ionized calcium in the blood reached abnormally high levels, which would be considered clinically significant on Earth. PTH levels were depressed indicating this hormone is not responsible for the calcium release. Data also demonstrated a difference between the response of men and women. Investigators hypothesize that the bone unloading in weightlessness leads to increased bone resorption, which in turn increases the levels of circulating calcium ion, decreasing the PTH level and thereby reducing the intestinal absorption of calcium. However, an important role is also played by the blood pH, which unexpectedly is reduced in the astronauts in flight, and which plays an important role in the release of calcium from protein (Arnaud, 1994). Animal experiments play an important role in the understanding of changes in bones in space flight, but are complicated by the use of growing rats for the investigations. Bones are not all effected the same way by flight, nor are all parts of bone effected similarly. Rat bones grow more slowly in space, and the bone structure is somewhat disorganized, but the effect is seen largely in singly caged rather than group caged animals, suggesting a non-mechanical explanation (Holton, 1994a,b; Roberts et al., 1987).

Experiments have been conducted to study the effect of space flight on the human immune system at the cellular level. Skylab 2 and 3 data indicated that lymphocyte responsiveness was markedly decreased on the day of recovery, but Skylab 4 data were not conclusive. The medical significance of this change is not yet clear. One lymphocyte experiment conducted on SL-1 was continued on SLS-1. SL-1 results indicated that lymphocytes are sensitive to gravity; however, the mechanisms of the effect of microgravity were not understood. Further investigations on Spacelabs D-1 and SLS-1 helped to clarify the situation somewhat, showing the importance of the surface area exposure of cells, as influenced by sedimentation on Earth, but still failed to explain why lymphocyte activation is reduced in weightlessness. The SLS-1 protocol involved studying both lymphocyte proliferation and kinetics. The investigators found that lymphocyte function was not affected by weightlessness but that the function of their activators, the macrophages, is depressed. These macrophages, which normally act as an accessory to T lymphocytes by activating them, appear to produce lower levels of Interleukin 1 (IL1), which is the activating substance. It appears that the macrophages must aggregate to produce IL1 and microgravity may affect aggregation, at least in vitro. The health implications involve the possible reduced effectiveness of lymphocytes in fighting infection (Cogoli, 1993).

The absence of a steady gravitational pull on the linear accelerometers (the otolith organs) of the vestibular system had been expected to produce disorientation and nausea in space. The problem was only recognized widely after the Apollo program, in which the increased roominess and ability of astronauts to make large movements apparently led to disturbances. The incidence of crew members with reported symptoms of motion sickness early during orbital flight now approaches 70 percent. Postflight difficulties in locomotion and posture were also noted in some astronauts upon returning to Earth. Investigations on Skylab demonstrated that, following several days of adaptation, astronauts were remarkably resistant to motion sickness provoking stimuli, both inflight and postflight. Intramuscular injections of promethazine are currently used to control motion sickness symptoms in flight, but no validated predictor of space motion sickness has yet been found.

The otolith system, or linear accelerometers in the inner ear, of course, do not function as usable gravity receptors on orbit. In order to determine how the nervous system copes with the need to stabilize the eyes during head movements and to maintain spatial orientation, a series of tests of eye movements and posture were begun on SL-1 and continued through Spacelabs D-1, IML-1, SLS-1, and SLS-2 (Figure 3). A four meter long linear “sled” showed that subjects did not rely strongly on otolith stimuli for orientation during motion on orbit (Arrott et al., 1990). The “rotating dome” test provided the first objective indication of the nervous system’s substitution of visual and tactile cues for the no longer valid inertial cues, and of the carry over of this visual dominance postflight (Young et al., 1986, 1993). The unique situation of space flight allowed explanation of several aspects of vestibular function that are normally hidden by gravity. The direct thermal influence on semicircular canal function was demonstrated to be an important part of the caloric test commonly used in clinical evaluation of patients with inner ear problems (Scherer et al., 1986). The elusive “dumping” of eye movements associated with head pitching after rotation was shown to be a gravity sensitive effect (Oman and Balkwill, 1993). Even the simple reflex involved in preparing for the landing from a jump is altered with exposure to weightlessness (Watt et al., 1986). The sensory conflict theory of space motion sickness was developed to explain symptoms associated with head movements in space as well as on boats and airplanes. Besides altered function of the vestibular system, weakness of the “antigravity” muscles in the legs and changes in the vestibulospinal reflexes add to postural instability postflight. There is wide variability in the perception of “vertical” in space. Some evidence of changes in the

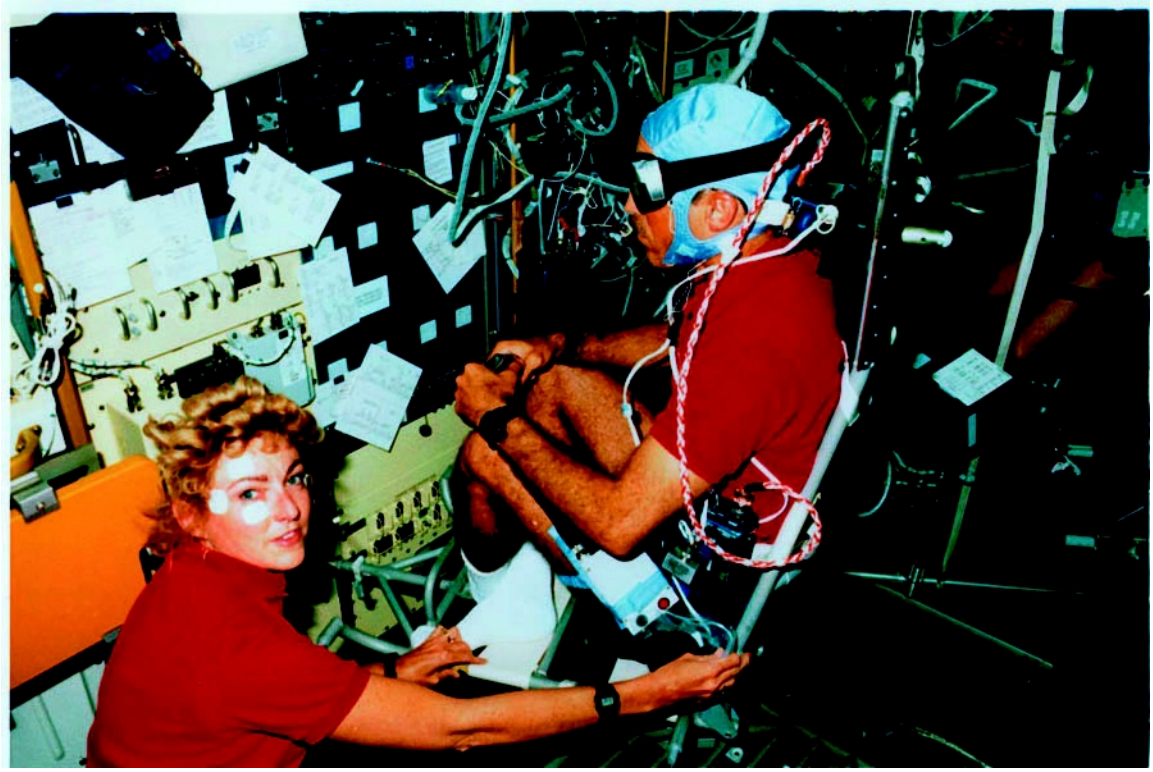


Figure 3. A simple hand operated rotating chair serves to stimulate the vestibular system in space. An Accelerometer Recording Unit is attached to the subject's cap, and his eye movements are measured with surface electrodes. (S40-211-020)

structure of the vestibular end organ itself, at the level of neural connections, has been observed in rats and could be associated with the neurovestibular adaptation process (Ross, 1993).

Plant studies have shown an unexpectedly high sensitivity to small gravitational forces, as a plant's roots grow downward and its stem grows upward. The mechanisms for such gravitropism are important not only for basic biology, but also for the eventual development of closed life support systems including the growth of crops in space.

A wide variety of animals have been flown in space, both to observe their behavioral and physiological reactions and for use in inflight experiments. Frogs, fish, flies, jellyfish and spiders have all demonstrated some measure of adaptation to weightlessness or to development in the weightless environment. Many of the results were surprising to the Investigators, including the tendency for fish to endlessly swim in "outside loops" or for jellyfish to metamorphosize normally in weightlessness. Monkeys have only been flown on the Shuttle/Spacelab flights one time, on SL-3, and are not currently scheduled for further flight on manned missions. Rats, on the other hand, have proven to be a useful and convenient experimental animal, and have been flown both in the mid-deck and in the Research Animal Holding Facility in the Spacelab module. Invasive experiments on rats, both in-flight and following flight, can elucidate the mechanisms underlying human system changes.

For example, the inflight dissection, injection of radioisotopes and repeated blood draws from six rats on SLS-2 permitted scientists to determine the underlying biology associated with parallel astronaut experi-

ments concerning reduction in red blood cell production, muscle atrophy, bone loss and vestibular reorganization (Figure 4). Rats are expected to be the primary research animal for the planned centrifuge facility project being developed for the Space Station.

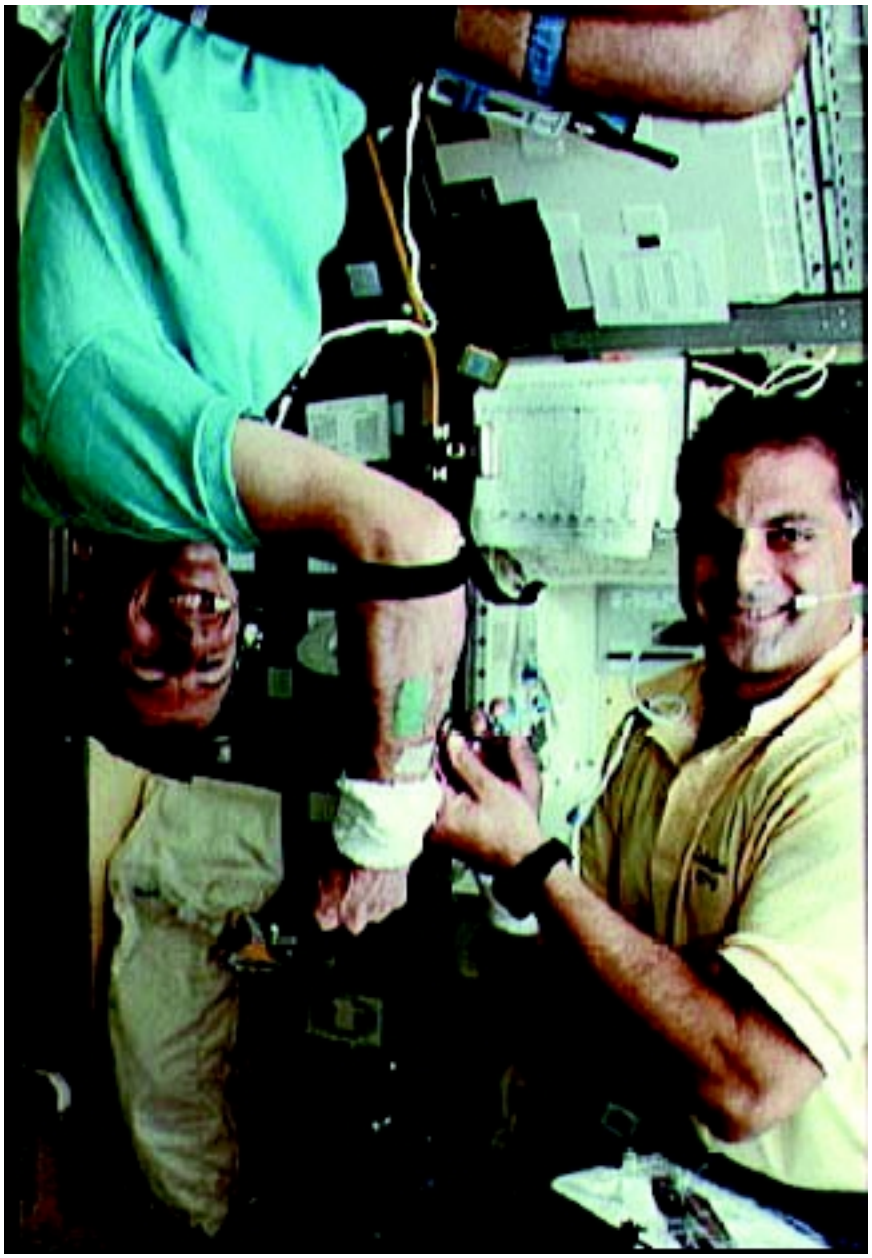


Figure 4. Blood drawn and injection of tracer materials serve to determine the basis for the reduced formation of red blood cells and the loss of calcium from weight bearing bones in space. (STS058-201-013)

Skylab raised the first questions regarding human adaptation to space flight. Since then, investigators have been gradually collecting physiologic data. The results from each mission are applied to support, modify, or develop new theories regarding each adaptation mechanism. Since Skylab the emphasis has been on performance of controlled scientific investigations, based upon testable hypotheses, with sufficient num-

bers of subjects (Figure 5). The availability of Spacelab, with its capability of performing a series of evolutionary experiments, on-board analysis, or sample storage facilities, and especially the opportunity to complement the astronaut measurements with animal experiments, has moved space life sciences ahead dramatically since its first flight in 1983. Many of the remaining problems require longer duration exposures than available with the Shuttle/Spacelab, and await the availability of the Space Station.



Figure 5. Principal Investigators monitor human Spacelab data and interact with the crew from the Science Monitoring Area at the Johnson Space Center. (The second investigator from the right is author LRY). (S85-43863)

The long-term goals of missions dedicated to life sciences (the SLS series) are to assure astronaut health and safety and to improve life on Earth by understanding the basic physiologic mechanisms involved in space adaptation. The area of crew health encompasses developing countermeasures to those adaptation mechanisms that can be potentially harmful on Earth, such as bone density loss and muscle atrophy. A complete understanding of the mechanism is necessary, before effective countermeasures can be developed. Scientists have collected data over the past decade and understand a little more about the mechanisms of space flight; however, results from each mission give more insight and lead to more questions regarding the mechanisms of adaptation to weightlessness. SLS-1 and SLS-2 were the first sister missions dedicated to life sciences research. Neurolab, which flew in April of 1998, explored a number of issues having to do with the brain and its reactions to space. Most of the other investigations planned for Spacelab were shifted to other carriers, including the Russian Bion (unmanned) flights for animals and the Shuttle/Mir flights this decade, which afforded the opportunity to study somewhat longer duration exposures of humans, in Spacelab, before returning to Earth. These and future missions that include life sciences inves-

tigations provide data needed to better understand human physiology in space, and may in turn lead to breakthroughs in life sciences research here on Earth. The life sciences community expect to play a major role in the long-duration research exposures available on the international space station.

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*A portion of this work was supported by NASA Grant NAS9-16523, and by the National Space Biomedical Research Institute through a cooperative agreement with NASA (NCC 9-58).

Dr. Muriel Ross

First of all, I would like to thank NASA and NIH for their support for the research that I've been able to do through all the years. I also want to thank NASA and their international partners for providing this wonderful platform, the Shuttle, on which we could carry on science. The payload specialists and astronauts must also be thanked for their important roles. It's just a big cooperative effort.

Today I have the pleasure of telling you about three important results that we have had studying the vestibular system, or gravity sensors of the inner ear. There are only three points I want to make, although I will show you some visual verification.

The first thing we found even while we were doing ground-based research, which is very essential to do space research, was that the wiring pattern of the gravity sensors was very different from what was expressed in the textbooks. That finding still stands. In fact, it was this finding that drove me into computer-based imaging. The finding had to be demonstrated in some objective way.

The second thing learned is that that the peripheral vestibular gravity-sensing system is tremendously plastic. It exhibits adaptation to weightlessness and to hypergravity. This was not understood when I began my space research.

The newest thing really is that there is a change in the protein making machinery of the cell. I think there is going to be a lot of molecular biology done to clarify these particular changes in the vestibular and other neuronal systems in response to weightlessness, because gravity sensors just stand in for the rest of the nervous system.

Since we have a mixed audience I really do have to start at the beginning and indicate what the gravity sensing structure looks like.

The membranous portion of the inner ear lies in the temporal bone. To give you some perspective, if you had a dime and laid it across the membranous structures of the inner ear, the dime would just about cover the structures. The inner ear contains an auditory part and a vestibular part, which is for balance. The end organs that are gravity sensors are in this structure called the utricle and in the sacculus. The other endorgans have to do with angular acceleration.

Of course, it was my thesis that because this is a gravity sensor and you are going into weightlessness, there would be changes in the neural connectivity of this organ. What we have concentrated on is the utricular macula. To give a perspective again, this macular structure in its entirety would be about as large as a period at the end of a sentence in newsprint. In order to study it adequately, we have to use transmission electron microscopy. Since we haven't found any payload specialist or astronauts willing to give up their inner ears, we work on rats as our model system. Fortunately, macular structure is essentially the same in all mammals.

The engineers among us will realize that gravity sensors are bio-accelerometers. There is test mass of little crystals which are particles of calcite with organic material in them. It is thought that it's the motion of these crystals of different sizes over the macula that stimulates the receptor cells and their nerve endings.

As this test mass moves, and we believe it moves discretely, structures called stereocilia bend. This is the stimulus to the receptors, which then will communicate the input to the nerve fibers that carry the information back to the central nervous system.

When I started this work, I had no reason to disbelieve what had been published about the ultrastructure of the macula. According to the first work published in 1956, type I hair cells were innervated by an expanded nerve ending called a calyx. Type II cells lack a calyx. It was thought at the time that the type II cell received an independent innervation from smaller diameter nerve fibers. Feedback had also been described, but it was thought to arise entirely in the central nervous system and to end on type II cells and on the calyces of the type 1 cells. The basic idea was that you had two types of cells, both communicating independently with the central nervous system. The first time any of the information from these two cells was brought together was thought to be in the central nervous system. I was finding something very different, based on my ultrastructural work. This was that type II hair cells lacked an independent innervation. Instead, the cells were supplied by branches of calyces and from the intramacular primary vestibular afferents. For example, figure 1 illustrates a computer-generated image of one of the sensory cells (in red, type II hair cell) of the macula, together with the nerve fiber endings on it. These endings all are branches of calyces or other nerve fibers (Figure 1).

Later, upon going back into the literature, I learned that Lorente De Nó had already described (in 1931) processes coming off the calyces and sometimes off the nerve fibers. His work was, however, largely forgotten. If anybody had paid any attention to Lorente De Nó's work, we wouldn't have had a long history of belief that the vestibular information is first put together in the central nervous system.

Indeed, the maculae are parallel processing machines. They have direct and local circuits. The type I communication with a calyx is direct and type II connections to processes provide for local circuits. Some of the processes are feed-forward and others are feedback. For the engineers as well, I think you understand — at least it has been impressed on me — that an entirely feed forward system is unstable and that indeed feedback surely should be a part of this system. Feedback/feed-forward local circuits shape the output of the system.

On the basis of new knowledge of the wiring pattern, I predicted that the type II cells would show more changes in space than would the type 1 cells; they just communicate very differently than do the type 1 cells. This brings us to major finding number two, that gravity sensors are highly adaptive to new linear acceleration environments. Type II hair cells show the greater adaptive changes and may be the gravity-sensing cells.

The finding of great macular neuronal plasticity was already established by the SLS-1 flight study, where the synaptic mean number of synapses was increased compared to controls by landing day. This finding was reinforced by the results of the SLS-2 investigation, in which the results were replicated and expanded upon. The synapses that actually carry out the communications with the afferents leading to the central

nervous system are spherical and rod-like ribbon synapses. But remember, there is a feedback involved here.

Our new, Neurolab data indicate that the synapses have changed in number and are significantly different from basal controls by day 2 (tissues collected inflight). Significant changes in synapses did not occur in type I cells, only in the type II. There was a P >0.0001 level of significance in the difference between synapses in the type II cells of the sample taken inflight compared to the basal tissue collected at almost the same time. On day 14 in flight, the mean number of synapses was reduced from day 2. I should say we took these data from a different place in the utricle so that we could see whether or not we were biasing our effects by where we were sampling. It's a different part, the lateral part compared to the posterior area we did before. We are still seeing changes that are significant.



Figure 1. Sensory cell of the macula.

This finding of a greater mean number of synapses early in flight compared to later was predicted. The idea is that going into weightlessness is a perturbation to a gravity sensor. It has all its synapses set up for one G on Earth. In weightlessness the system goes into a bifurcation and should over- or undershoot the final mean number to be achieved when the system is fully adaptive to the new environment. Here is our first indication that the synapses may overshoot. This is the only piece of evidence that we have right now, but it is very promising. The data are still preliminary

The other side of weightlessness is hypergravity. We do work on a centrifuge to mimic hypergravity. It is very, very important that we do this because if the synapses increase in space, they should decrease in hypergravity. This is what we find as has been reported in our SLS-1 publications.

We also participated in the Space Life Sciences-Japan experiment with Kenneth Souza's frog experiment. We found no significant differences between synapses of frog utricular maculae collected in space, whether they were exposed always to weightlessness or had been placed in an on-board centrifuge at 1G. We later used the same mother to produce some more tadpoles to test for differences between ground controls and the 1 G study conducted on board the Shuttle. Remember, these are blind studies. The samples from inflight centrifuge tadpoles and ground controls were nearly identical. What I want to emphasize here are two things: 1) the tadpoles had not reached a critical period of development to show adaptive changes; and 2) the on board centrifuge is going to be absolutely invaluable as one of the controls that we use in space for comparison with ground controls. So I'm so delighted that we are going to have an onboard centrifuge.

I've now discussed wiring of the maculae and synaptic adaptation to space. The last major change to be discussed is in the laminated endoplasmic reticulum (ER), or what we call the "Nissl substance" of neurons. In SLS-1, we already had seen an indication that the Nissl substance is disorganized on landing day (within 5 to 7 hrs postlanding) but is completely normal in appearance by day 9 postflight. A similar finding was obtained from the SLS-2 study, which took the postflight period out to day 14.

In Neurolab, we switched strains (from Sprague Dawley to Fisher rats). Interestingly enough, the protein making machinery of the cells was a little different. In the type I cell from basal controls, the laminated ER appears to be fluffy, with the cisternae of the ER dilated. In type II cells, some laminar ER can be found. Many times ER is not there at all.

On day 2 inflight, laminated ER was hypertrophied. By day 14 inflight the laminae are greatly reduced in number. Thus, the protein making machinery of the cell is affected by spaceflight in these animals as it was in those of the SLS-1 and SLS-2 experiments.

The central question is "Why is this happening?" This may be physiological evidence of feedback in this system. The basis for this notion is work done in other neuronal systems. Sobkowicz has isolated the auditory system and put it in tissue culture. Synapses increase in number in the inner hair cells of this tissue in culture. Since the auditory endings are cut off from their cell bodies and from central influences, she believes that it is feedback from the nerve endings left peripherally that influences cellular changes in the synapses.

There is experimental evidence that laminated rough endoplasmic reticulum is also regulated transneuronally. In the avian system, the nucleus magnocellularis suffers disorganization of its laminated ER following

removal of the organ of Corti. This effect is reversible if the auditory nerve is simply blocked and then the blockage is removed. In the central nervous system, Pullen and his colleagues have shown that the laminated ER of cat thoracic motor neurons hypertrophy upon partial deafferentation.

Thus, I am very excited about the work that I have been able to do in the space environment and am grateful for the privilege. I believe that there is a great future for Space Station. I'm only sorry that its inaugural use for research is too far into the future for my participation. We need young people to enter spaceflight research and learn the molecular basis for the adaptive responses to weightlessness.

Thank you for your attention.

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Dr. Kenneth Baldwin

It's a pleasure to be here today. Following up on some of the comments made earlier, I want to personally thank the team of research scientists and administrators at Ames Research Center. These individuals get little recognition, but I wouldn't be here talking to you today if it weren't for the strong support that they have provided me in putting together the various missions that I have participated in.

Dr. Muriel Ross described her research on a small part of the body's anatomy that is about the size of a dime. I'm going to talk to you about the largest organ system of the body, the skeletal muscle system (Figure 1). I'm also going to address an issue that relates to a disease that, judging the gray hairs, the thinning hair, and the seniority of the audience, is a disease that we all are afflicted with, sarcopenia, or muscle wasting.

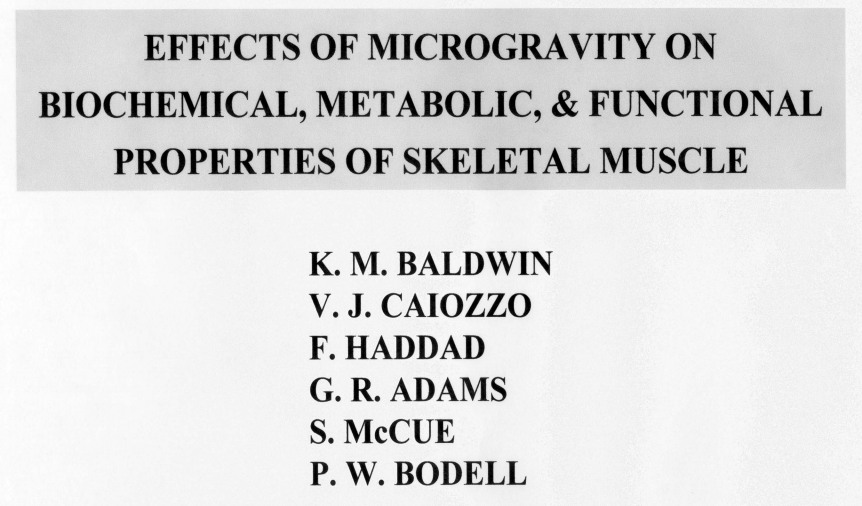


Figure 1. Title and investigators.

This is a very important disease and it can be studied in particular in the microgravity environment (Figure 2). It is depicted here in terms of its impact as it relates to aging. You have heard some of the problems that are also related with regard to the overarching issues that Dr. Larry Young pointed out.

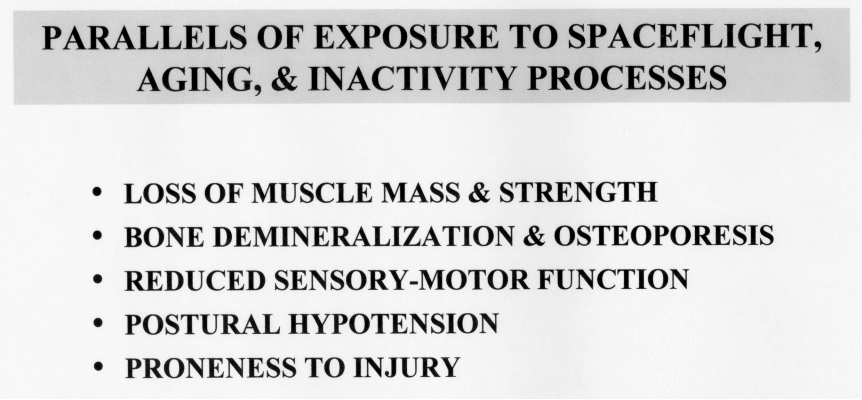


Figure 2. Parallels of microgravity exposure, aging, and inactivity processes on the human body.

In order to understand the changes in structure and function in skeletal muscle, I'm going to focus on a motor protein called the myosin heavy chain (Figure 3). This has been used in a series of studies. This protein is the most abundant protein we consume on a daily basis if you are a protein eater. If you eat animal products or fish products, that's the primary protein that you are consuming, but it is an important protein that really directs the overall way in which our muscles operate.

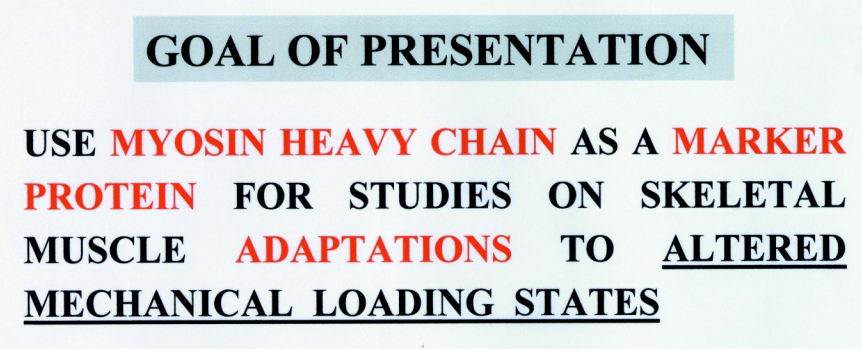


Figure 3. The goal of the presentation.

I want to emphasize, just as Muriel Ross did, that muscle plasticity is an ongoing thing (Figure 4). Just as she described all of the plastic changes that are going on with the organelles within the inner ear, we're dealing with the same type of problem. As one gets involved in space or is fortunate enough to fly, what is happening is that we are adjusting the quantity and the quality of the type of proteins that are expressed in this system.

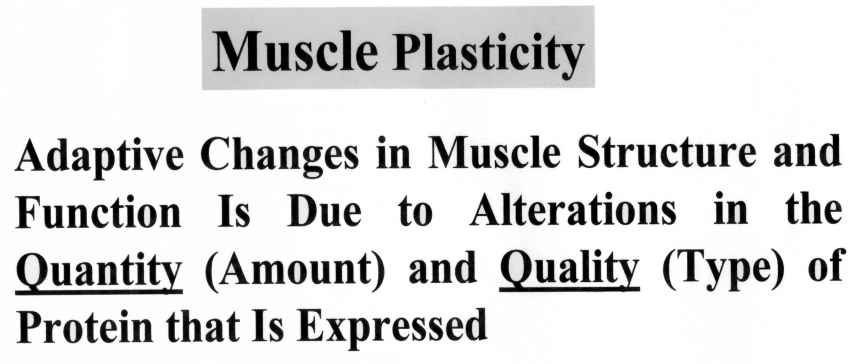


Figure 4. Description of muscle plasticity.

We can study this protein plasticity by looking at how the muscle structure and function and the genes that are expressing these structures and their inherent function due to a process that we call protein turnover (Figure 5).

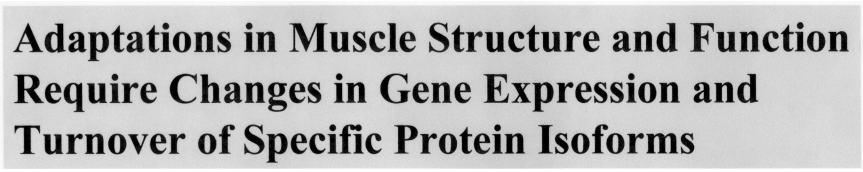


Figure 5. Protein turnover.

Whether you realize it or not, as you are sitting there in the audience your skeletal muscle proteins are undergoing a continuous change in expression (Figure 6). You have genes that are encoded for proteins. They transcribe a message. The message translates into the expression of the protein, and this is followed by the degradation of the protein.

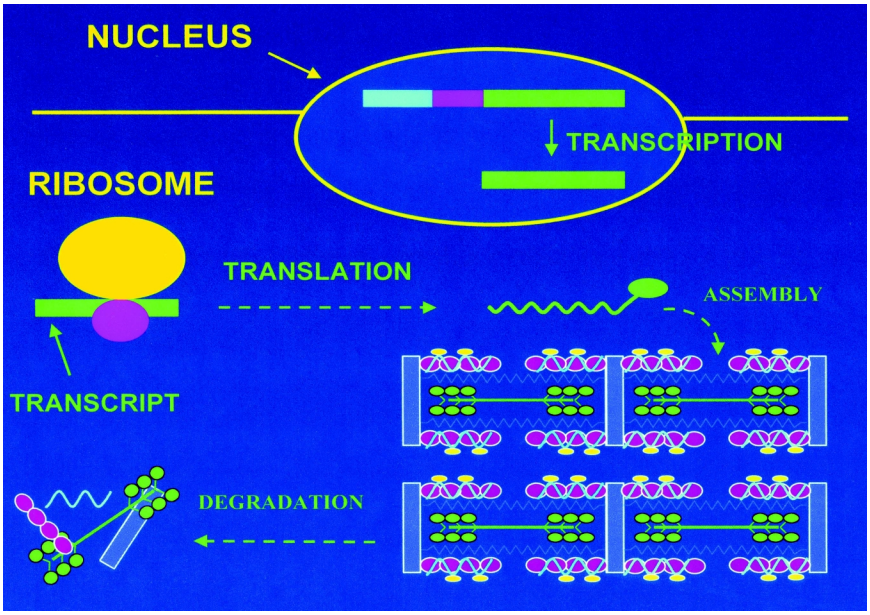


Figure 6. Protein expression in the cell.

What you see here on a daily basis is that you are making and degrading proteins and turning them over, but when you are exposed to the microgravity environment, this process is altered dramatically. What we end up seeing occurring is that we are impacting on how certain genes are transcribing, how they are being translated, and how their protein products are being degraded. In a nutshell, what we are doing is decreasing the synthetic capacity within the muscle system and increasing the degradation processes. So there is a tremendous remodeling and an imbalance of protein structure and function taking place.

I show this diagram to you to show this remarkable postural exercise, which I can sort of emulate for you — I'm not too old to do that (Figure 7). The reason why we can basically experience these unique types of movement patterns is that all of our muscles contain what we call slow type fibers that are designed to oppose gravity. In order to maintain the integrity of these slow types of fibers, loading state is essential in maintaining the structure and function of the specific motor genes that we call the slow types of motor genes.

When we look at the complexity and we include the nervous system, we can see that we functionally organize our various muscle fibers and, in particular, the slow motor protein types of fibers, into a functional unit that we call the slow motor unit (Figure 8).

We have faster motor units that express a different type of motor protein that makes these muscles contract a little faster. Then, we have high-power motor protein fibers that allow for individuals to perform burst activity. So while I'm standing here, I am primarily recruiting out of my nervous system my slow motor unit protein pool. When I start jogging across the stage here, I increase the intensity, and I begin to recruit

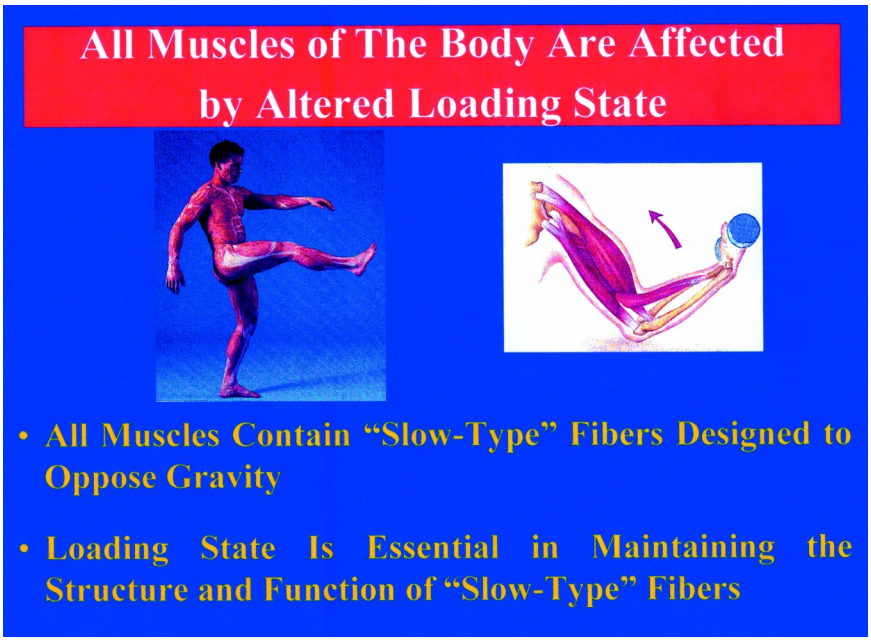


Figure 7. Slow-type fibers at work in the human body.

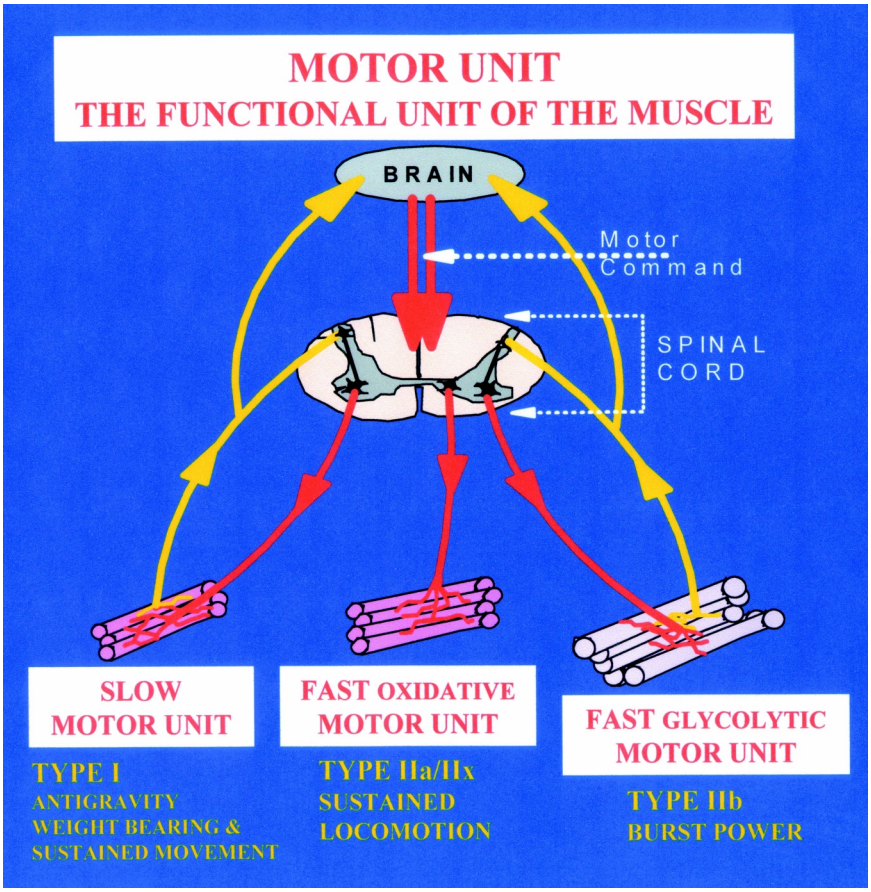


Figure 8. Muscular motor units.

these types of motor proteins. When I do a “Michael Jordan” slam dunk, I am recruiting these high power but fatiguing fibers.

We have a very complex motor unit pool. What we are studying in our space flight is what is happening across these types of fibers and how the primary motor genes are being expressed in these various fibers.

We can take ourselves down into the milieu of the fiber components (Figure 9). I just want to emphasize that when we talk about fast fibers, while we can get this high burst activity, we pay a price for this. The price is that we expend a lot of energy in performing these powerful activities.

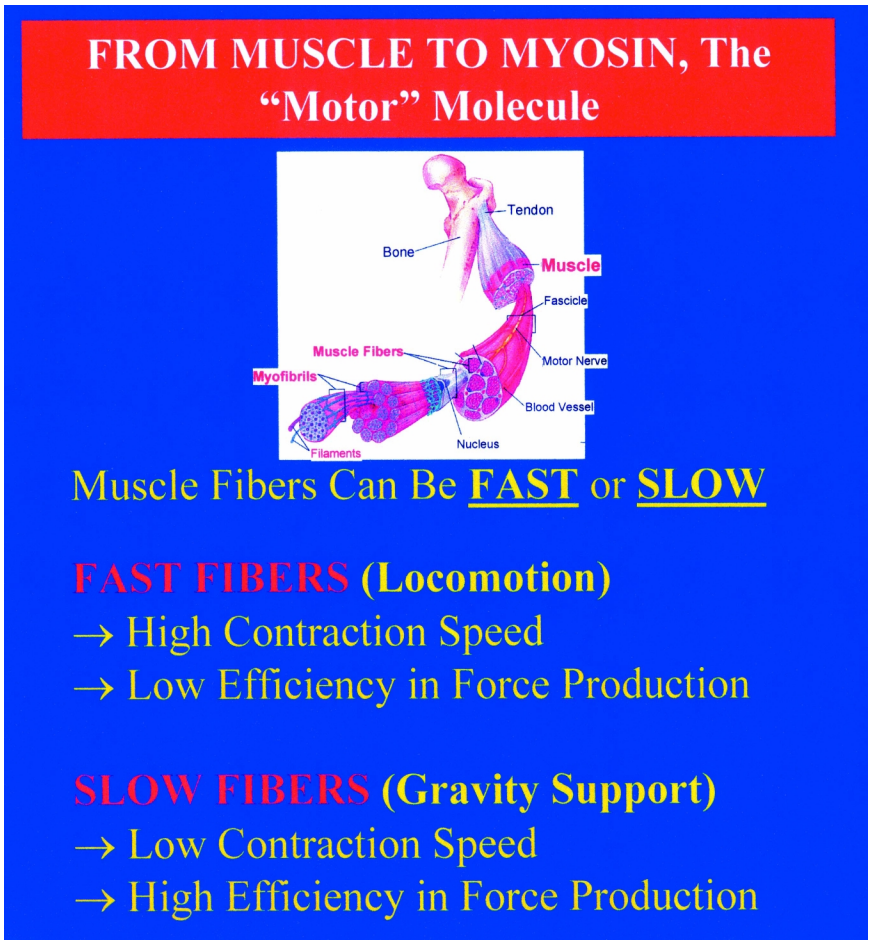


Figure 9: Two types of muscle fibers.

In contrast, the slow fibers that we use for gravity support are highly efficient in the management of force production (Figure 10). So, when we begin to change the relative size of these fibers, and if we cause switching in the types of fibers that are being expressed by changing expression of these genes, we are remodeling. In a nutshell, we’re going to have a tremendous reorganization to what is occurring.

Here we have the schematic of the molecule that we are studying at the regulation of gene expression (Figure 11). We see here the primary flavors that we know are expressed. I just want to show you that the slow type of myosin is the one that is expressed in those antigravity fibers that we have been alluding to.

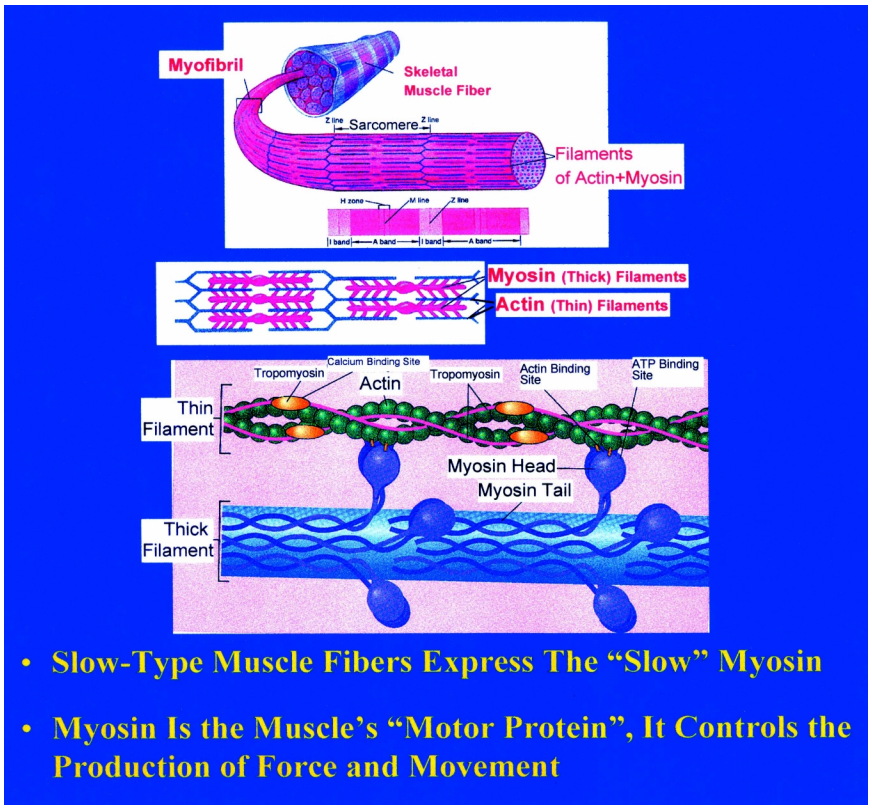


Figure 10. Myosin in muscle fibers.

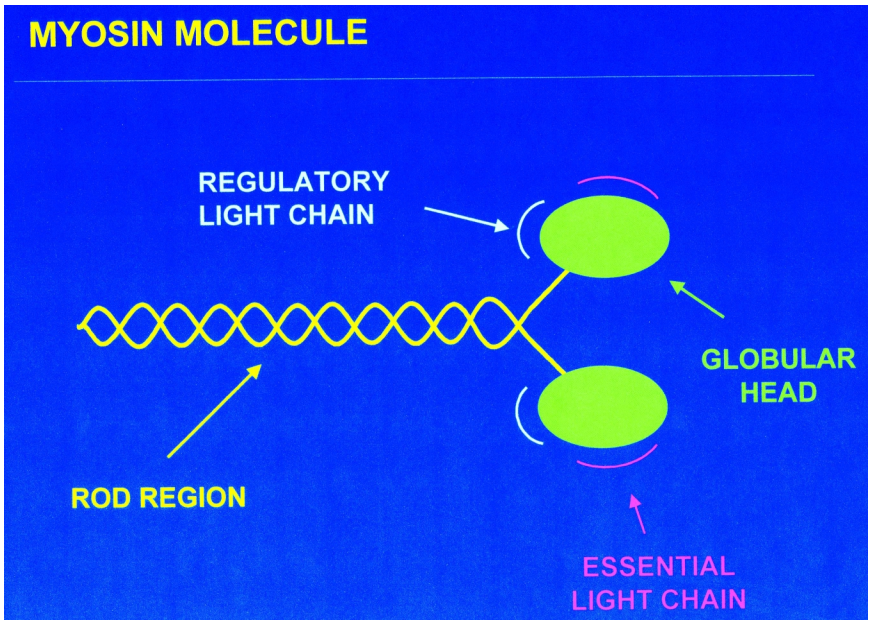


Figure 11. Schematic of a myosin molecule.

This protein here, the myosin, is the type of motor that we would express in those fibers that we used for slam dunking; and when we are using these fibers, these are intermediate types of myosins that are ideally suited for prolonged locomotor activity.

This shows you that we can develop techniques to isolate and quantitate these fibers in our research either at the single fiber level or down at the whole muscle level (Figure 12). When we begin to look at the astronauts' experience in this microgravity environment, what we are basically seeing over time is the remodeling of the skeletal muscle system.

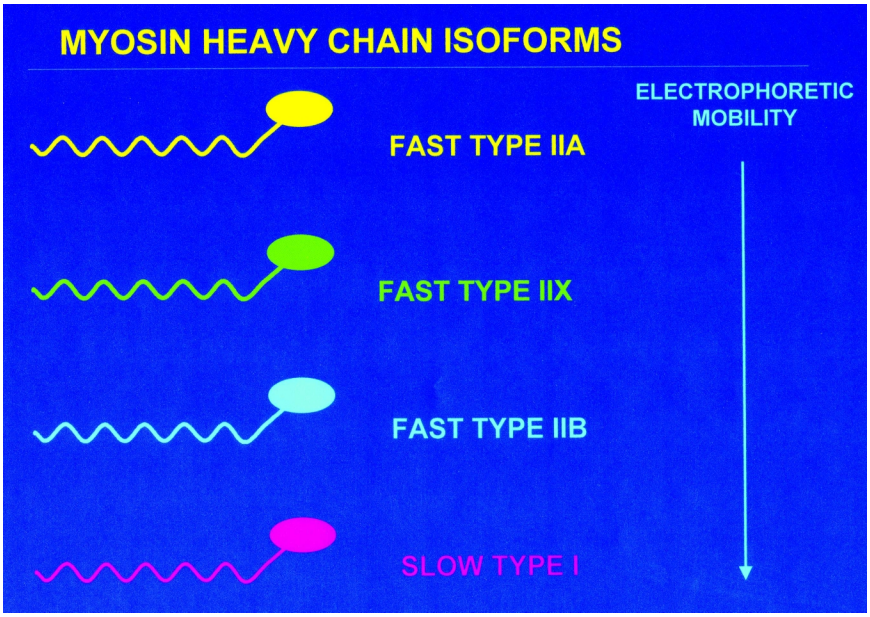


Figure 12. Myosin isoforms.

In order to become more invasive, in order to look at the molecular structure in the internal milieu within the fiber, we have elected to use our friend the rodent. One of the advantages of using the rodent as a model in space is that the muscle machinery that we see in these interesting little creatures is identical to what we have in our own human muscles. But interestingly, the turnover of the proteins in these animals is much faster than we have in our human muscles. Thus, six days or eight days or 15 days in space translates to many weeks in space for the adults. What we can see in the ideal configuration of the Spacelab experiments that we have experienced is a very unique model in order to extrapolate for more long-term experiments in space.

Take, for example, a typical laboratory rat. If you spend time like I do watching them in their normal cage habitat, you discover that these animals spend a lot of time in a bipedal stance. They will use their tails to basically feel and as a pair of eyes behind them. They spend a lot of time basically in a bipedal position as they explore about. Then you watch a rat that has just come back from nine days in space. Basically, he is saying, "Woe is me, what the hell hit me when I landed here." They are hunkered down; they're flat; they're spread out; they use their tails very flat for support. They are very, very unstable.

If we look at their motor behavior, we would see that their bipedal stance is dramatically reduced. We feel that there is a disruption to the homeostasis of the muscle system. We would see that their voluntary walking speed is dramatically reduced. So these animals, from a general behavioral standpoint, are showing the same instability that we see in our human subjects when they return from their space experience.

If we want to get into a little bit more structural detail here, these two muscles, the soleus and the vastus intermedius, are the two primary muscles — one is in the lower leg; the other is in the thigh region — that we use for most of our basic posture (Figure 13).

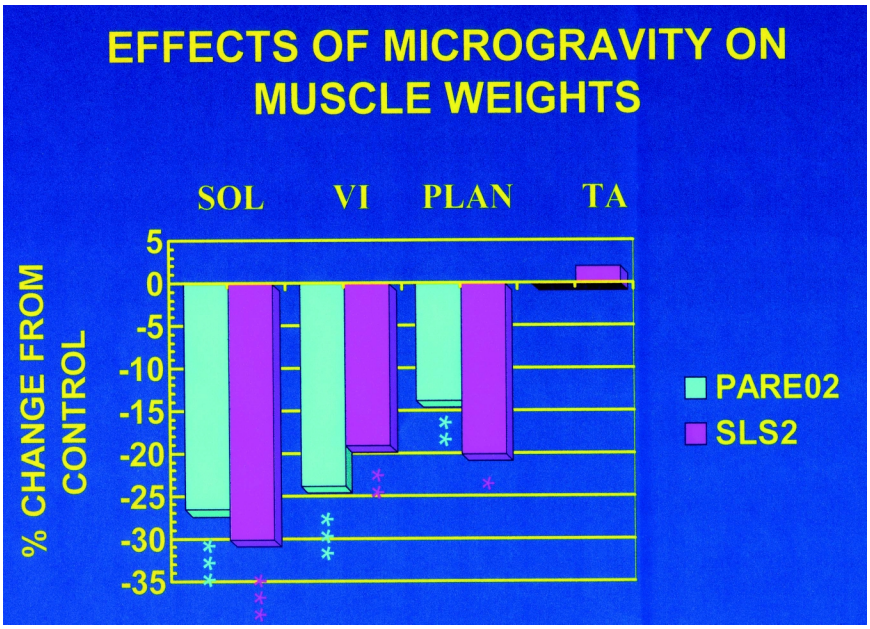


Figure 13. Muscle loss in microgravity.

You can see that in as little as six days in space there is about a 30 percent loss in the muscle mass in these two types of fibers. Those muscles that are used more for locomotion also atrophy. Those types of fiber that we don't use in our normal weight bearing activity show very little response to space. All the muscles that we use typically in our daily routines are highly sensitive to this unloading state that we experience in space.

In the time frame that this occurs, if we were to look at this happening on Earth, you wouldn't be able to reproduce it in terms of the mass of muscle loss that is occurring within this short period of time. There is no model to simulate this on Earth in terms of the degree of muscle wasting that occurs.

If we look at the contractile machinery, i.e. the myosin and the actin proteins that make up the basic motor proteins, you can see that the concentration doesn't change much (Figure 14). But, if you look at the net loss of these proteins, there is a tremendous loss in these proteins. Hence, there is a tremendous loss in the muscle mass of these fibers.

When we look at the ribonucleic acid (RNA), which is basically the machinery that we use in terms of translating or synthesizing protein, we are losing this protein mass but we are not disrupting the machinery that is used in the assembly line to make these proteins (Figure 15). So there is something going on with how we signal the genes to manufacture the proteins, how we operate the assembly line, and what we do to degrade these proteins that are being disrupted in the microgravity environment.

What we are seeing here is an inability to maintain muscle mass (Figure 16). What this slide shows is basically an immunoblot for the fast fibers in a typical antigravity muscle. You can see that in a typical

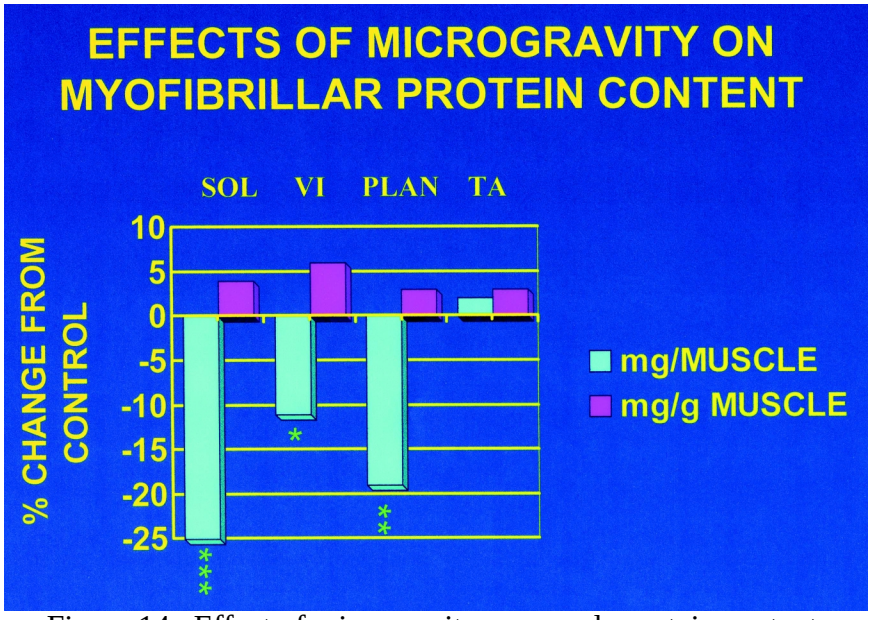


Figure 14. Effect of microgravity on muscle protein content.

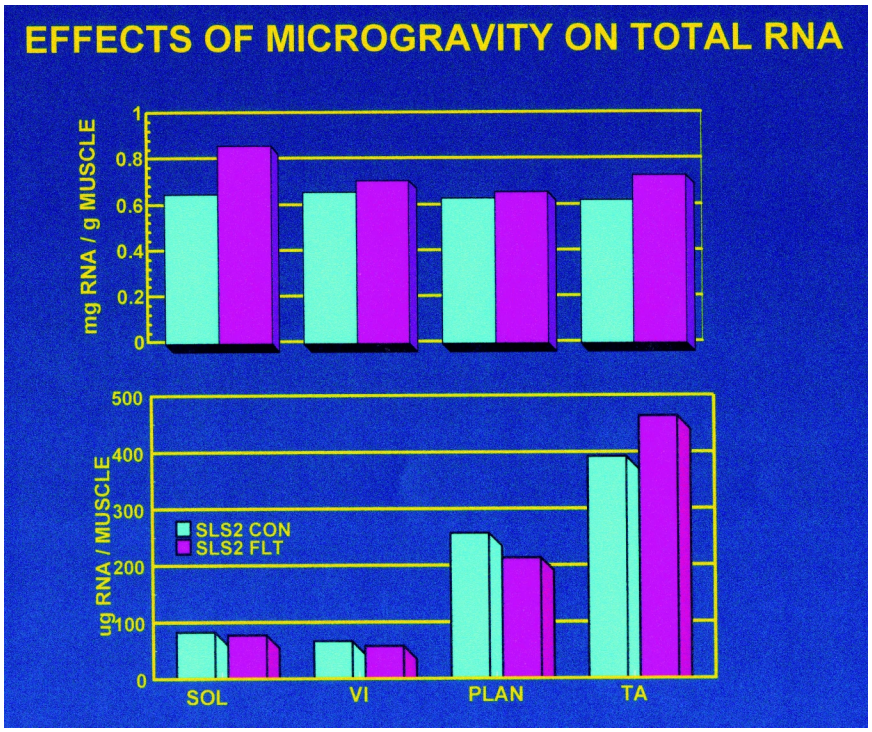


Figure 15. Microgravity effects on muscular RNA.

antigravity muscle most of the fibers don't stain for these fast motor myosin heavy chains. This is typically what we see in a muscle such as the soleus.

After as little as six days in space, you can see that we are now transforming more of these slow fibers into a faster phenotype. This faster phenotype is such that we are now beginning to express proteins in motor genes that are not as effective for supporting the animal in a weight bearing state.

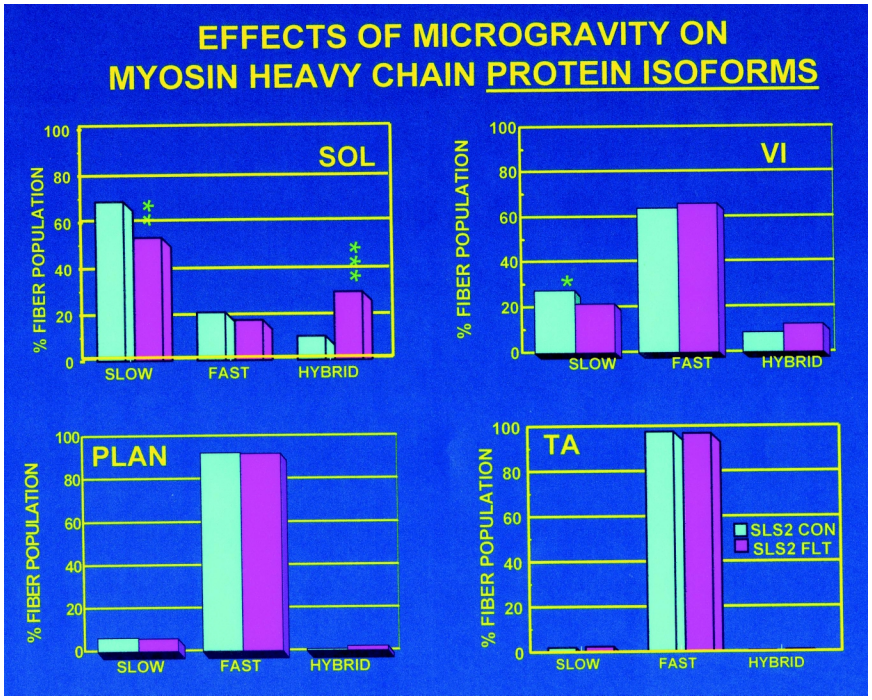


Figure 16. Immunoblot for fast muscle fibers in microgravity.

These data merely show you this by putting some quantification on it (Figure 17). What we see here is that most of the fibers are becoming a hybrid, that is, they express both slow and fast proteins. This is a unique feature that we found over all four of our experiments in space. You don't convert these slow fibers into a truly fast fiber, but the space environment remodels each of these fibers so that they are expressing various combinations of both slow and fast myosin.

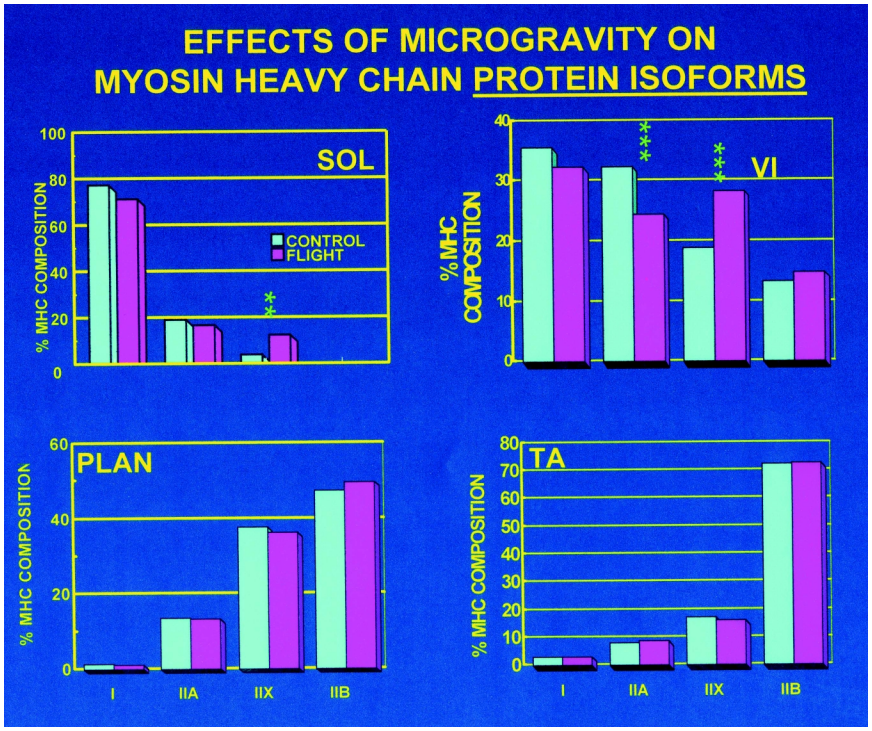


Figure 17. Transformation of slow fibers to fast phenotypes in microgravity.

If we look at the specific genes and we look at the mitochondrial ribonucleic acid (mRNA), which is going to give us an idea in terms of how the genes are being regulated, we see phenomena that suggest that we are shutting down the transcriptional pathways for these genes that represent the slower forms and we are turning on the genes for the fast motor proteins (Figure 18). So we are working at the molecular level in terms of how we are controlling these genes. We are atrophying the muscle and we are now switching the type of protein that is being expressed in the muscle to regulate the contractile apparatus.

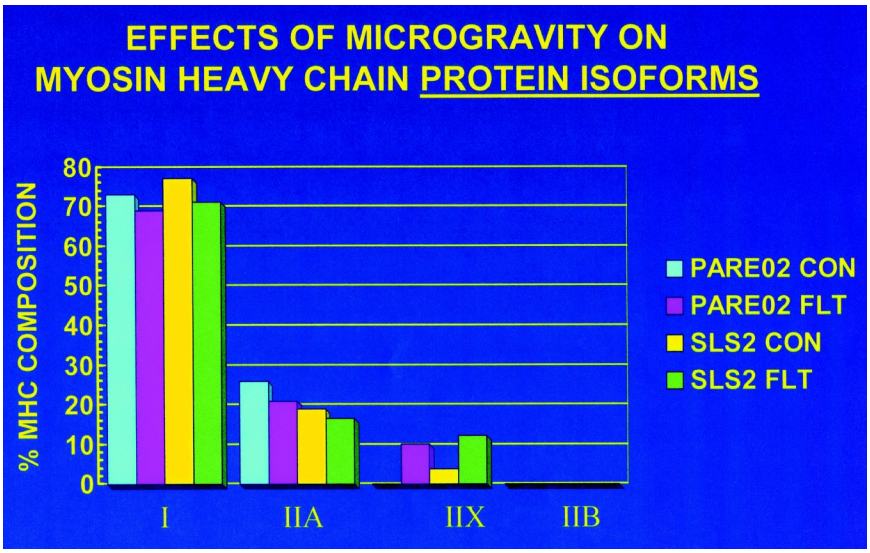


Figure 18. Microgravity remodeling of muscle fibers.

These data show you what happens in terms of the functionality of the muscle (Figure 19). What we see here is that just as we saw a loss in muscle mass, there is a loss in muscle strength and what we call specific tension as a result of this. This suggests that we are actually decreasing strength beyond what we are basically losing in terms of muscle mass, suggesting that there may be neural properties that are also being compromised in this reduction in strength.

At the same time, we are making these muscles function in an intrinsically faster way, and while this may help somewhat in terms of force and power output, it's actually remodeling the muscle such that now we are expressing more of a faster property (Figure 20). This suggests that the turnover of energy in supporting this is becoming enhanced as well, which is probably not as desirable for maintaining antigravity function.

We show that the relaxation properties of the muscle are also becoming faster. The importance of this observation implies that we are now cycling another energy pathway, the cycling of calcium that turns the contraction apparatus on and off (Figure 21). Thus, now we are making our cross bridges work faster, we are cycling calcium faster, and this is what is becoming an energy drain for the operation of the muscle fibers.

What this basically translates to in a functional state is that by switching the muscle and creating a faster muscle and an atrophied muscle is that now when the nervous system has to generate a force output, let's

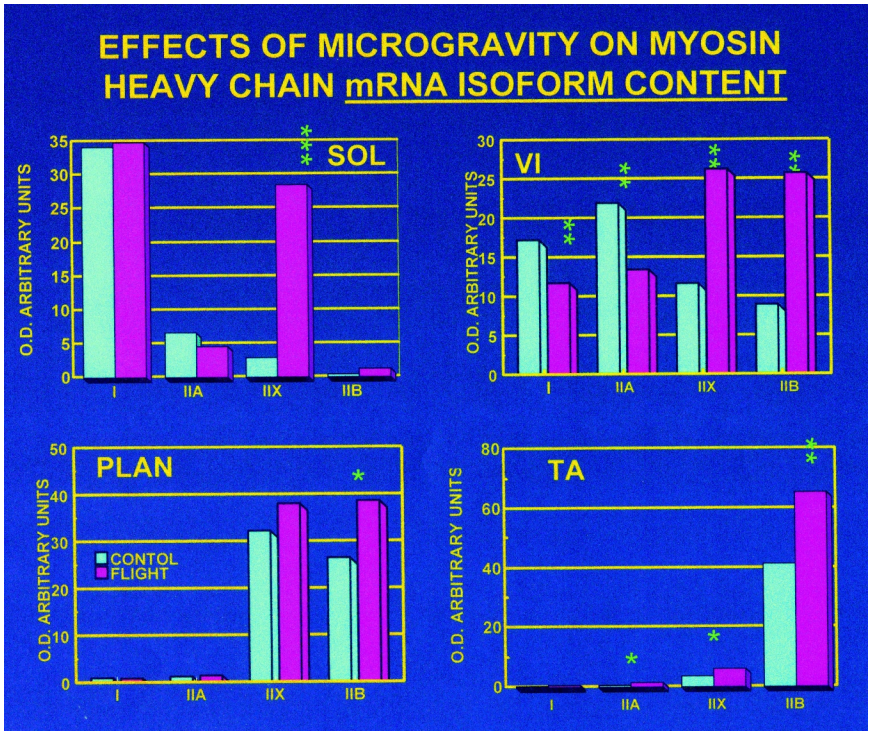


Figure 19. Microgravity effects on muscular mRNA.

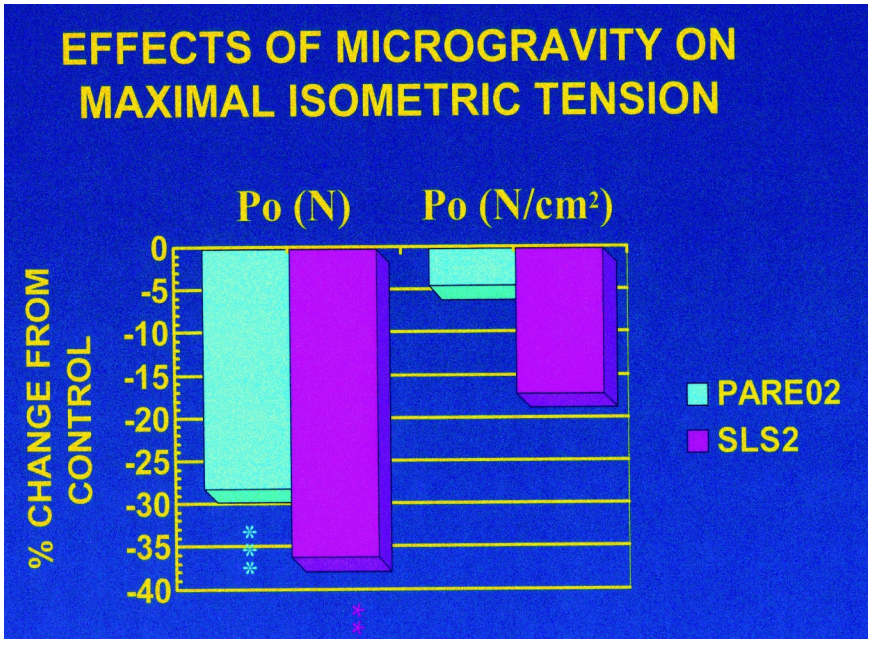


Figure 20. Effects of microgravity on muscle function.

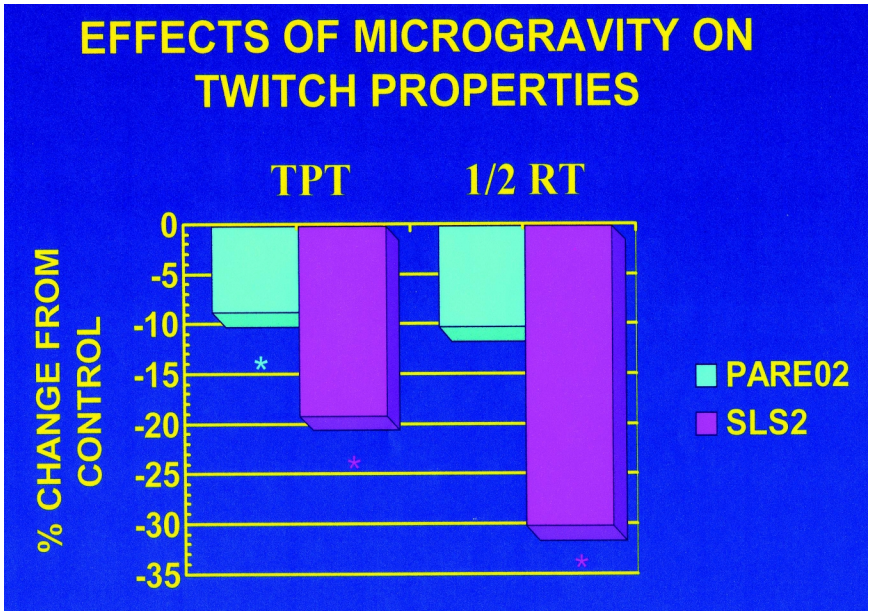


Figure 21. Effects of microgravity on the calcium contraction engine.

say in this case 63 percent of the normal force output, there has to be a remodeling of how the nervous system operates in order to fire the neurons at a higher frequency, in order to achieve a desired functional output (Figure 22).

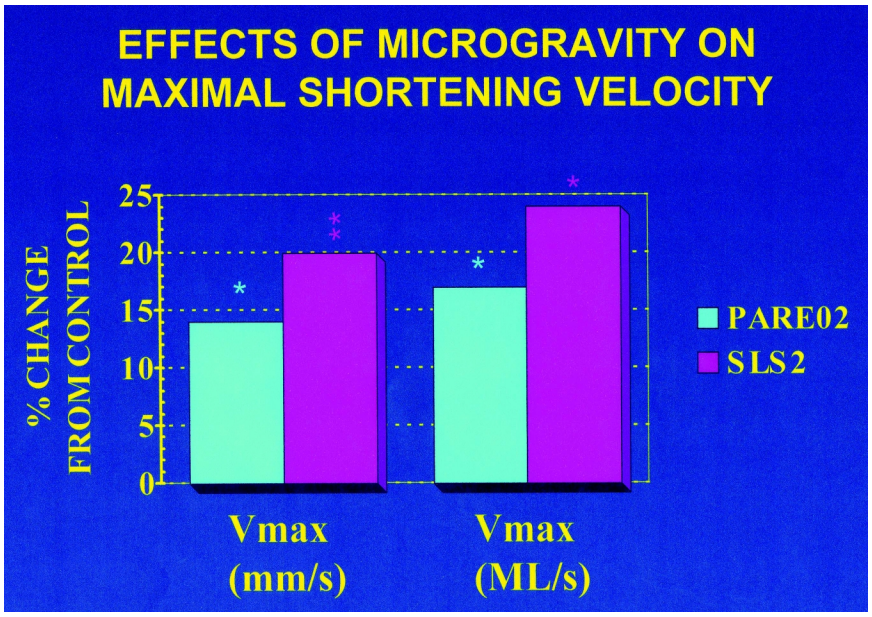


Figure 22. Effects of microgravity on muscle shortening velocity.

We think that by changing the structure of the muscle and its intrinsic functional properties, it's making tremendous demands on how the nervous system must remodel itself in order to operate, in order for an individual just to maintain his/her capability when the individual returns from microgravity to a one G environment.

I want to mention a few points about one of our missions in which we were able to study the primary organelle in the muscle that synthesizes the energy that we use in order to drive the machinery. We studied how these organelles process an end product of carbohydrate metabolism. We found that there wasn't really any disruption to the capacity of how the muscle fibers process carbohydrate substrate energy, but we found significant reductions in the way in which the muscle processes long chain fatty acids of lipid substrate. This is important because by reducing the capacity of the muscle to use fat as a form of fuel, it forces the muscle to use more carbohydrate. Since the muscles can only store a limited amount of carbohydrate, we think that this should enhance the fatigability of the muscle.

We are concerned that if this is occurring in the astronaut subjects — it needs to be validated in astronauts — and they get into performing high levels of work in a gravitational field and their ability should be compromised, they would really have to make some adjustments in their carbohydrate in the diet. This is basically not occurring if you monitor the diets of most astronauts today. They are not eating enough calories to begin with, and, in particular, they are not consuming enough carbohydrates.

We see that what is occurring here is that there is a remodeling of the muscle. It imposes on how the motor units within the muscle should be in their redesign, how they are atrophying, and how they are going to create a faster phenotype. By switching to these faster motor pools we are not having the muscle appropriately designed to oppose work on gravity.

I know that I have moved very quickly here because of a lack of time. I want to take an opportunity to show you a couple of results from the exciting Neurolab project that we had because it was the first time we had an opportunity to fly developing animals in space at critical windows in their developmental scheme.

In a nutshell, the point that I want to emphasize here is that we know that individual muscles, in the absence of a weight-bearing activity to continually stimulate them, do not grow much beyond what we see at a basal state (Figure 23).

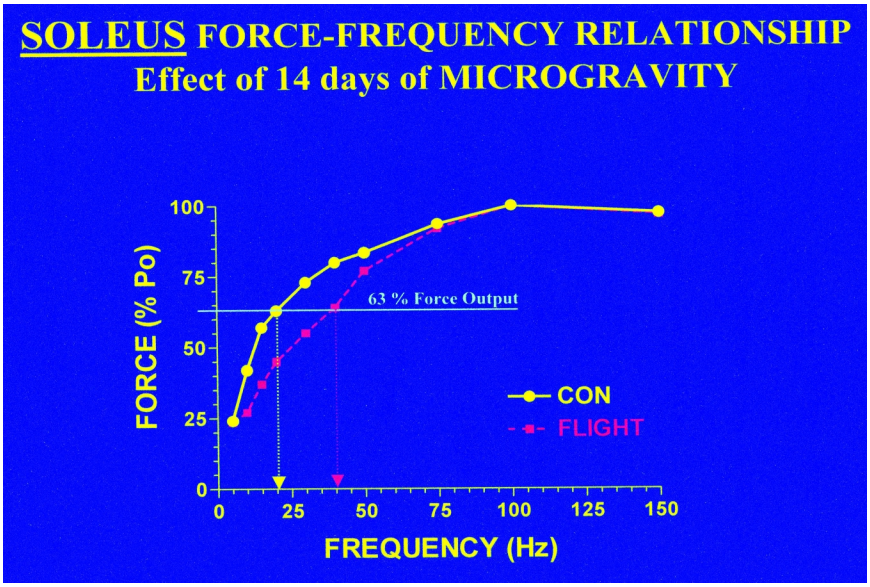


Figure 23. Force-frequency relationship after 14 days of microgravity.

These are data obtained at the age of seven days when these animals are launched, and after 23 days the ground-based animals show large muscle growth, but that muscle growth is being compromised in a normal animal (Figure 24). If we take thyroid hormone away, we can now begin to petition the importance of thyroid hormone in its interaction with gravity in this growth pattern.

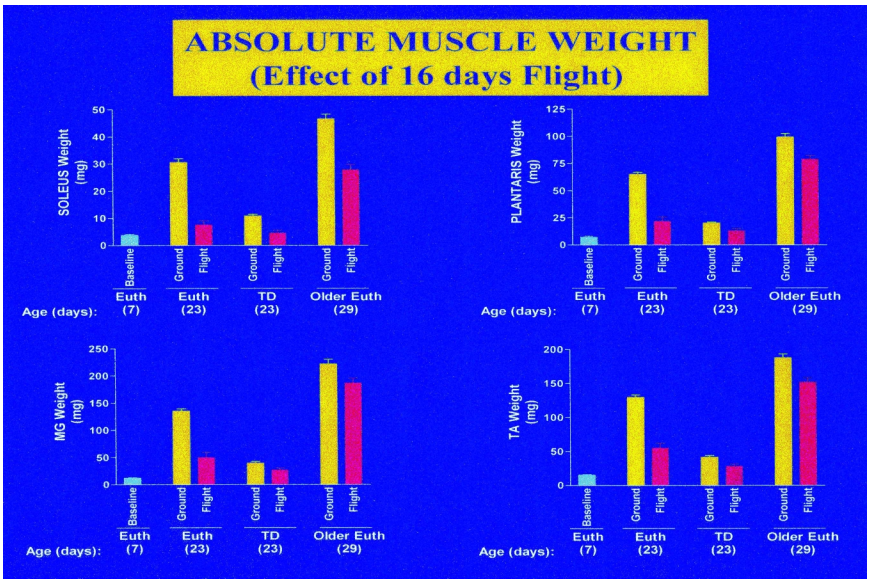


Figure 24. Effect of microgravity on muscle weight.

We were very excited about these data. Even when you normalize muscle weight to body weight, we see that there is a tremendous reduction in the capability of a growing animal to express normal growth in these muscles. One of the culprits in this process, we think, has to do with a growth factor called IGF-1. That gene, which can be expressed in the muscle and is an important gene for stimulating the normal growth pattern of the muscle, is being repressed so that less peptide is being synthesized (Figure 25). Hence, it's probably playing a role in terms of how the whole growth process within the muscle is occurring. This shows the profound impact of what microgravity does to a young growing animal.

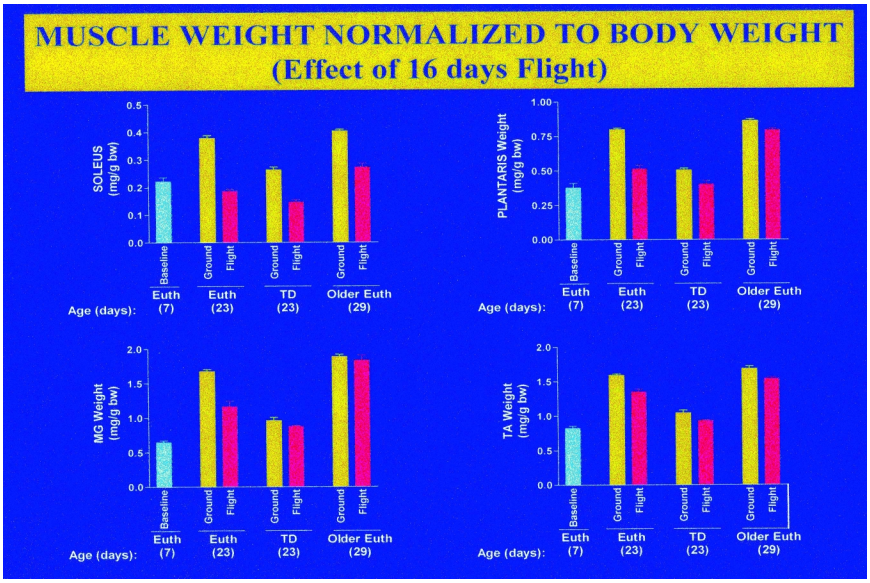


Figure 25. Muscle weight normalized to body weight.

The other point that I would leave you with is that when we look at how the slow motor units or the slow motor genes are being maintained, we find that they are not evolving to a normal phenotype in the microgravity environment. In order to turn on these genes for the normal maturation of the muscles that support our day-to-day activities in space, this system is being compromised in the absence of weight bearing activity (Figure 26).

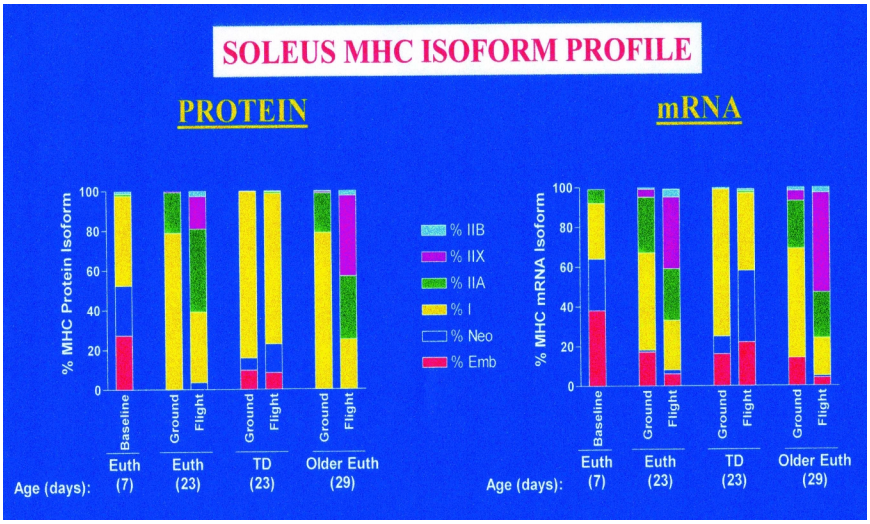


Figure 26. MHC isoforms.

In conclusion, I want to end by saying that skeletal muscle of both adult and developing animals is highly dependent upon gravity for its structural and functional integrity. Reductions in muscle mass, strength and metabolic capacity coupled with slow to fast transformations in the contractile protein phenotype reduce the capacity. In our view, the more work one performs in opposing gravity, the greater the functional benefit as a countermeasure. Therefore, whether you are an astronaut going into space or if you are an individual going through the aging process, I suggest you use it as much as you can, or you're going to lose it (Figure 27).

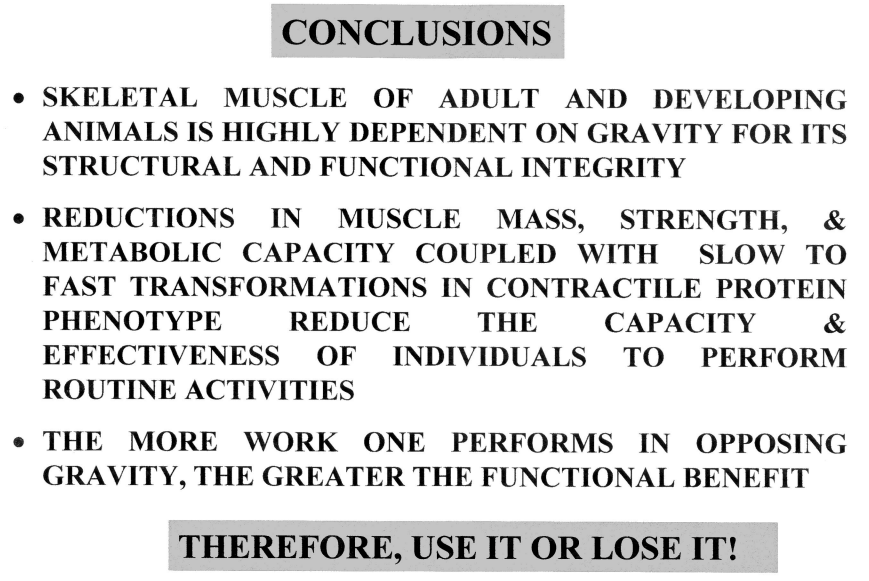


Figure 27. Conclusions regarding microgravity and muscle function.

Dr. Mary Anne Frey

The Neurolab Spacelab Mission, which flew from April 17-May 3, 1998, was devoted to research on the nervous system. It was NASA's contribution to the 1990's Decade of the Brain. Neurolab provided a valuable transition from the Life Sciences research that had previously been completed on Spacelab to future research on the International Space Station.

One reason for this is the very close cooperation that was developed early in the planning stages of Neurolab with our Partners. Such cooperation will be essential for successfully conducting life sciences research on the International Space Station. The international partners on Neurolab included the European Space Agency (ESA), as well as the space agencies of Germany and France (DLR and CNES), the Japanese space agency (NASDA), and the Canadian Space Agency (CSA). These international partners provided important hardware, or equipment, that made some of the research on Neurolab possible. In addition, they supported the investigators and research from their countries. Neurolab principal investigators and co-investigators represented countries throughout the world. Our other partners on Neurolab were U.S. national partners: the National Institutes of Health, the National Science Foundation, and the Office of Naval Research. They helped make Neurolab possible by supporting the ground-based research of the U.S. investigators. In addition, the National Institutes of Health managed the international scientific peer review.

Furthermore, the experience gained on previous Spacelab missions enabled us to successfully fly a very sophisticated set of life sciences experiments on Neurolab. I will mention a few of the procedures and techniques that were performed in space flight for the first time on Neurolab. For the first time, we recorded directly from nerve cells of humans, that is, the crew members. We recorded from sympathetic nerves in their legs during, as well as before and after, space flight. We also directly recorded from the central nervous system of rats during the Neurolab space flight. And, we recorded from the vestibular nerve of fish. We performed surgery on animals with the animals recovering during the Neurolab flight. (This was required for one of the experiments, but it also provided knowledge that will help us prepare for the future possibility of surgery in space on humans.) Fetal mice were delivered during the flight for another research protocol. And, finally, the first in-space flight double-blind crossover study was conducted on Neurolab. This was an investigation of the efficacy of a low dose of melatonin to improve sleep and performance in space flight. Our next speaker will describe more about that study.

In fact, the Neurolab investigators are scheduled to report their preliminary results from the mission April 14 to 16, 1999, here at the National Academy of Sciences. You've had previews from some of the investigators already. Our next speaker was a co-investigator on another Neurolab investigation, and I'm pleased to have the opportunity to introduce him.

Dr. Rod Hughes received his Ph.D. in cognitive and behavioral neuroscience from Bowling Green State University in Ohio. While in Ohio, he studied the effects of melatonin on sleep, a topic related to his research on Neurolab. He conducted postdoctoral research at the Oregon Health Sciences University and became an Assistant Professor there. Later, he was Director of the Clinical Biology and Sleep Laboratory at Brooks Air Force Base for the U.S. Air Force. Dr. Hughes is now a faculty member at Harvard Medical

School, where he is a co-investigator on the Neurolab STS-90 sleep experiment, as well as on the sleep experiment that was performed on the STS-95 flight.

In closing, I would like to say that it has been an honor and a rewarding experience to be the Program Scientist for Neurolab. I have greatly enjoyed working with the investigators, with our partners, and with the many people in NASA whose diligent efforts made Neurolab such a successful mission.

Dr. Rod Hughes

The following presentation may be in stark contrast to the wonderful audiovisuals that you have been seeing this afternoon and throughout the day. I'm giving this presentation on a moment's notice. Fortunately, I was able to have some of our slides faxed and some people here were able to make them into transparencies.

I'm going to talk about sleep in space. Apropos to this topic, I am giving this presentation at the end of a very long day. We will soon dim the lights, and for those of you travelling from multiple time zones, you may have the added disadvantages of last night's insomnia compounded with attempting to remain awake during what may be your biological nadir of alertness. Therefore, if you see me taking notes up here, you'll know why. I'll be watching all of those falling asleep and collecting data unobtrusively.

In addition to the prevalence of insomnia and daytime subsequent sleepiness being prevalent at international meetings such as these, insomnia is also very prevalent in astronauts attempting to sleep in space. This is evidenced not only by empirical research aboard Skylab and aboard Spacelab, but also research done on long duration missions by the Soviet and European space agencies. Anecdotal evidence also supports the findings that astronauts and cosmonauts can have significant difficulty sleeping, particularly when sleep is scheduled to occur outside of the internal rhythms responsible for promoting sleep.

Hypnotic medications are the most frequently prescribed medications on space missions. In fact, hypnotic prescription rates of astronauts in space are much higher than in age-matched controls and even higher than in older individuals that we study here on Earth. Therefore, the prevalence of insomnia as well as the use of hypnotic medications in space are quite high. There may be several reasons for the impairment of sleep in space, some of which I will discuss next.

Dr. Dijk was the project leader of the Neurolab Sleep experiment and I will be showing some of the overheads that he made up for a previous presentation to NASA (Figure 1). I was the project leader of our experiment on the STS-95 mission. In one subject aboard the STS-95 experiment, we simply extended the Neurolab protocol. In another subject aboard STS-95, we completed a case study on sleep and circadian adaptation to space flight in an older subject.

So why might astronauts have difficulty sleeping in space? First of all, microgravity itself may have some effect on the internal physiological processes that are responsible for promoting sleep that we have yet to discover. There are two primary processes responsible for promoting sleep and wakefulness. One is a homeostatic process, which can be described essentially by a near linear function. The homeostatic process is characterized by a sleep need or sleep debt that accumulates as a function of how long one is awake and subsides or is "paid off" as a function of how long one is asleep. There is a second, circadian, process responsible for promoting sleep and wakefulness. The circadian process is responsible for ensuring that the internal rhythms responsible for promoting sleep and wakefulness remain entrained or in synchrony with the 24-hour environmental light-dark cycle. The homeostatic and circadian processes interact to maximally promote sleep at night and wakefulness throughout the entire day.

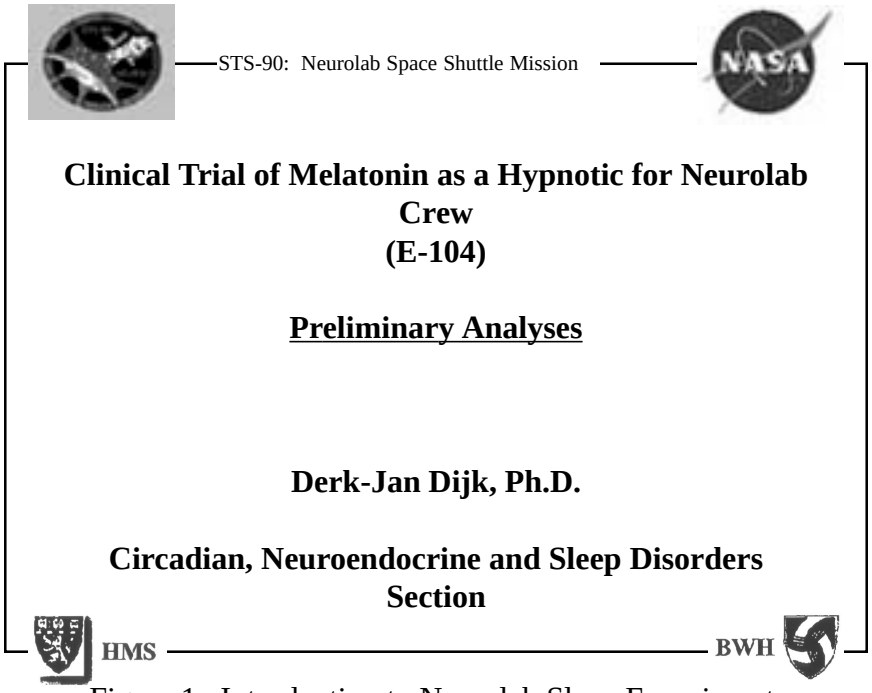


Figure 1. Introduction to Neurolab Sleep Experiment.

Humans and some other diurnal primates are unique in that they have sustained bouts of wakefulness throughout the day and sustained bouts of sleep throughout the night. This is the result of a complex interaction between these circadian and homeostatic processes. As I mentioned, spaceflight may have some yet undiscovered effect on one or both of these processes or on their interaction.

In addition, the fact that astronauts are sleeping in such a novel environment may have a significant impact on the amount and quality of their sleep. It has been demonstrated many times on Earth that sleeping in a novel environment can adversely effect sleep. It is for this reason that sleep researchers bring subjects into the laboratory for at least one adaptation night to allow subjects to become acclimated to the new environment and to overcome what is known as the “first night effect”. If sleep in the laboratory is different than sleeping at home can you imagine the potential impact of sleeping in space?

Certainly astronauts are not able to obtain the same behavioral cues for sleep or the same comfort level for sleep that they are used to on Earth. Rather than being snuggled down in their bedding, for instance, astronauts are often strapped to the wall often with their arms floating up by their faces. The noise in the spacecraft is also much higher than to which they are accustomed during sleep episodes. In addition, temperature fluctuates to a greater degree during the sleep period in the spacecraft. To be sure, the new sleep compartments that have been implemented for some crew members aboard the Space Shuttle and will be carried over to the International Space Station have reduced the adverse impact of many of these adverse environmental influences on sleep.

Besides environmental factors, I can think of very few situations that would be more exciting than living in space. This excitement may make it difficult for crew members to “wind down” at night in anticipation of sleep. The various personal benefits of space flight, such as looking out the window during personal time and also the mission demands of a very compact work schedule may also constrain the time allocated for relaxation and sleep.

In addition to these factors, sleep may also be scheduled to occur out of phase with the internal rhythms responsible for promoting sleep. Much like shift workers on Earth, astronauts are often required to function on imposed sleep-wake schedules that are out of phase with their internal rhythms that promote sleep and wakefulness.

Over the past 10 years, researchers in our lab and other labs throughout the world have discovered that the endogenous hormone melatonin may be strongly associated with the internal processes responsible for promoting sleep at night. In normally entrained individuals, circulating levels of melatonin are high at night and very low, if not undetectable, during the day. This endogenous hormone may be responsible for communicating a hormonal message of nighttime darkness. This putative temporal cue has been associated with the nocturnal decline in core body temperature and some have argued that melatonin may mediate sleep itself.

We, and others, have demonstrated that in some circumstances daytime melatonin administration can promote sleep. It appears that melatonin optimally promotes sleep when it is administered and sleep is attempted out of phase with endogenous nocturnal melatonin production. Therefore, melatonin may be a sleep-promoting substance that is more natural than traditional hypnotics. Melatonin has also been shown to have less side effects than the traditional hypnotics that are taken in space such as Restoril, Valium, and Ambien. Although melatonin may not be as effective as the benzodiazepines for promoting sleep in all conditions, it may be tailor-made for promoting sleep in individuals who are attempting to sleep out of phase with their internal circadian rhythms.

Based upon these findings, Dr. Charles Czeisler, the Principal Investigator of our experiments and Dr. David Neri our Co-Investigator, proposed a Clinical Trial of Melatonin as a Hypnotic for Neurolab Crew. As Mary Ann [Frey] said, this investigation was the first placebo-controlled pharmaceutical study ever carried out in space.

The primary objectives of this investigation were to ascertain whether a very low dose of melatonin could be an effective countermeasure for insomnia, and indeed if it could, whether the improved sleep would increase waking alertness and performance.

Orbital mechanics and specific mission requirements required a substantial phase advance of crew member's sleep-wake schedule from the beginning to the end of the mission. This advance was divided evenly into an average 20-minute phase advance each flight day, requiring the crew to go to sleep and wake up 20 minutes earlier each day. It was hypothesized that over the course of two weeks this sleep-wake schedule would not cause dramatic misalignment between the internal circadian rhythms that promote sleep and wakefulness and the actual sleep-wake cycle (Figure 2). It was specifically hypothesized that the circadian rhythms of core body temperature, urinary 6-sulfatoxymelatonin (the primary metabolite of melatonin), and urinary cortisol in these crew members, would not be significantly out of phase with their behavioral sleep-wake cycle. Despite this relative circadian synchronization, however, it was hypothesized that space flight would result in a significant disruption of crew members' sleep, and that this insomnia would adversely affect next day neurobehavioral alertness and performance.

This experiment was originally carried out on four subjects during the Neurolab (STS-90) mission. The investigation was repeated in one subject aboard STS-95. For the four crew members aboard the STS-90

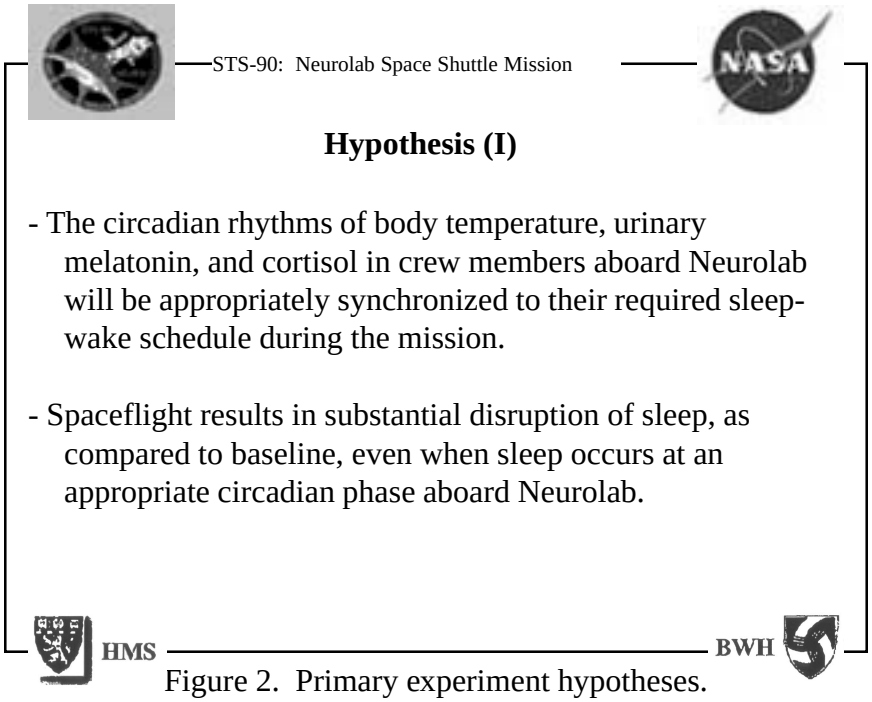


Figure 2. Primary experiment hypotheses.

and the one crew member aboard the STS-95, we additionally hypothesized that the administration of melatonin 30 minutes prior to bedtime would improve sleep (Figure 3). We also hypothesized that this improved sleep would increase subsequent neurobehavioral alertness and performance throughout the waking day.

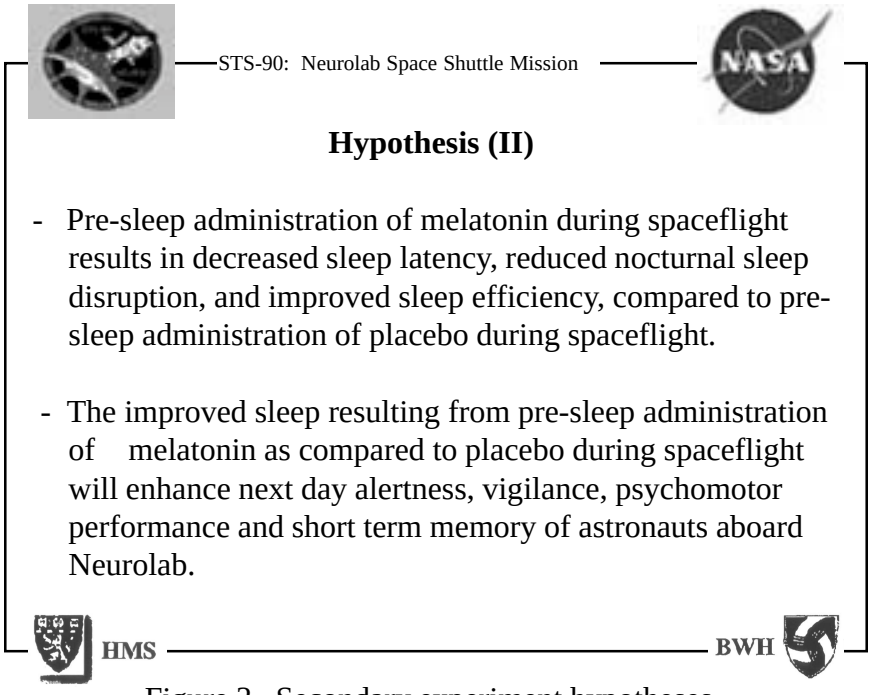


Figure 3. Secondary experiment hypotheses.

As Mary Ann [Frey] also said in her introduction, this experiment involved the development and implementation of equipment that had never before been used in space (Figure 4). Indeed, much of this equip-

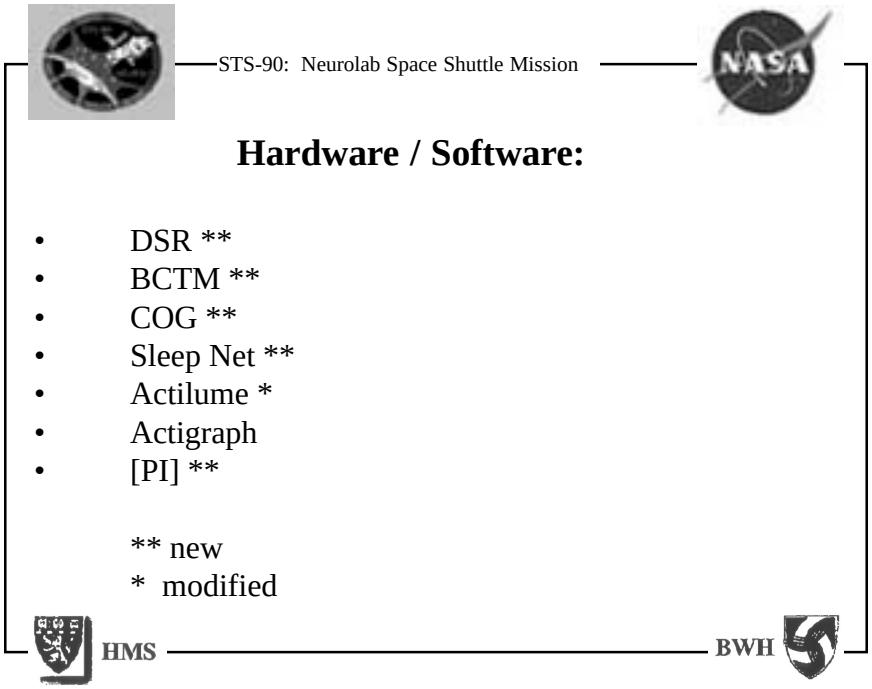


Figure 4. Neurolab Sleep Experiment hardware.

ment was either developed for the Neurolab mission or the development was significantly expedited in preparation of the mission.

Sleep was recorded on some nights using a Vitaport digital sleep recorder (DSR). The Vitaport digital sleep recorder essentially replicates a 400 to 500 pound fully operational polygraph found in clinical sleep laboratories. The development of this new technology has yielded a small portable device with the power and capacity to record sleep and other physiological variables in space.

Assessment of core body temperature is an important marker or indicator of the timing of the circadian clock, which in turn governs the timing of sleep and wakefulness. Rather than using rectal temperature to estimate internal circadian time, we used the Body Core Temperature Monitor System. Subjects ingested a pill containing a temperature sensor and a radio transmitter. This pill sampled core body temperature and transmitted this measurement, by radio telemetry, to a receiver that was worn by the subject. This non-invasive device allowed us to obtain an estimate of core body temperature every minute.

The neurobehavioral performance assessment battery is a newer version of the performance assessment that has been done on two previous Spacelab missions. This test battery, which included tests from the Neurobehavioral Assessment Battery developed by Dr. David Dinges at the University of Pennsylvania, was used to assess daytime alertness and performance.

The Sleep Net or e-Net, is also a new device (Figure 5). The e-Net was responsible primarily for holding the sensors in place. Each e-Net was custom fit to ensure proper placement of scalp and facial electrodes.

The crew members were assisted in the instrumentation of the e-Net and the verification of the quality of these very sensitive signals by the PI in the box. This software, developed by Dr. Larry Young and col-



Figure 5. The Sleep Net or eNet Neurolab hardware.

leagues at MIT and NASA Ames Research Center, uses artificial intelligence technology to assist crew members in ascertaining the degree to which they were collecting good physiological recordings.

The Actillume was used to quantify the amount of light to which crew members were exposed in the three main compartments of the space craft. The light-sensitive circadian clock uses environmental light exposure to ensure that our internal processes that promote sleep and wakefulness are in phase with the environmental light-dark cycle. Therefore, it is important to quantify the pattern and intensity of light to which these individuals were exposed.

The Actigraph is a small wrist-worn device that measures activity, affording the use of sophisticated algorithms to estimate how much individuals are awake and how much they are sleeping throughout each day.

The investigation included subject participants MS-1, MS-3, PS-1 and PS-2 of STS-90 and PS-1 of STS-95 (Figure 6). On STS-95 we carried out an additional case study on sleep and circadian adaptation to space flight in an older astronaut on PS-2. Multiple baseline assessments were made pre-flight at L-90, L-60,

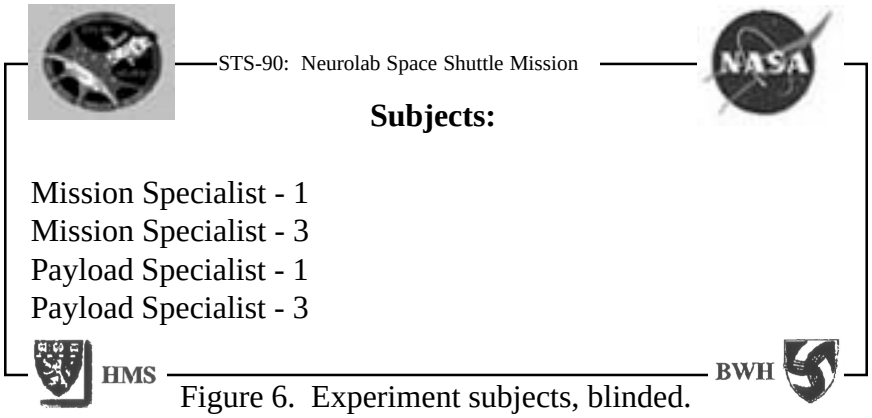


Figure 6. Experiment subjects, blinded.

L-30 and L-11 and post-flight until R+8 (Figure 7). At each of these baseline data collection sessions, sleep was assessed for several days with the Actigraph and sleep diaries. Core body temperature was monitored continuously for 48 to 72 hours. Complete digital sleep recordings were also made on at least two nights.

Date	Urine	COG	Sleep Study	Act/ Log.	Mel	Core	Scheduling Constraints
L-90							
	Subjects will perform the critical two-day protocol, including double-blind melatonin and placebo administration, two nights of fully instrumented sleep monitoring for all six subjects, URINE, COG, CORE, ACT, and LOG. To be performed in conjunction with other BDC activities.						
L-60							In the period L-66 to L-50 days.
	Subjects will perform the critical two-day protocol, including double-blind melatonin and placebo administration, four nights of fully instrumented sleep monitoring for all six subjects, URINE, COG, CORE, ACT, and LOG. To be performed in conjunction with other BDC activities.						
L-30							In the period L-36 to L-29 days.
	Subjects will perform the critical two-day protocol, including double-blind melatonin and placebo administration, two nights of fully instrumented sleep monitoring for all six subjects, URINE, COG, CORE, ACT, and LOG. To be performed in conjunction with other BDC activities.						
L-11-0							In quarantine period
	Wrist actigraphy every night. Three nights of instrumented sleep studies for all four subjects with COG performed on following afternoons, CORE, URINE.						

URINE: 24 hour urine collection, beginning with first void of first day, and ending with first void the following morning.
COG: Cognitive Performance Testing
Sleep Study: Polysomnography, with full instrumentation and recording.
ACT: Actigraph wrist motion monitoring, continuous recording.
LOG: Daily sleep log.
MEL: Drug administration. Subject will take a pill (placebo or melatonin) 15 minutes prior to retiring, and after any urine collection, in a double blind study.
CORE: Core Body Temperature. Block of continuous recording of approximately 32 hours.

Figure 7. Preflight data collection schedule.

Neurobehavioral alertness and performance was assessed on days following digital sleep recordings. From L-11 until eight days post-flight, sleep was recorded every night with Actigraph and sleep diaries (Figure 8). During the inflight phase of the mission, the 72-hour baseline recording sessions, including two nights of digital sleep recordings, were repeated once early in the mission and again later in the mission.

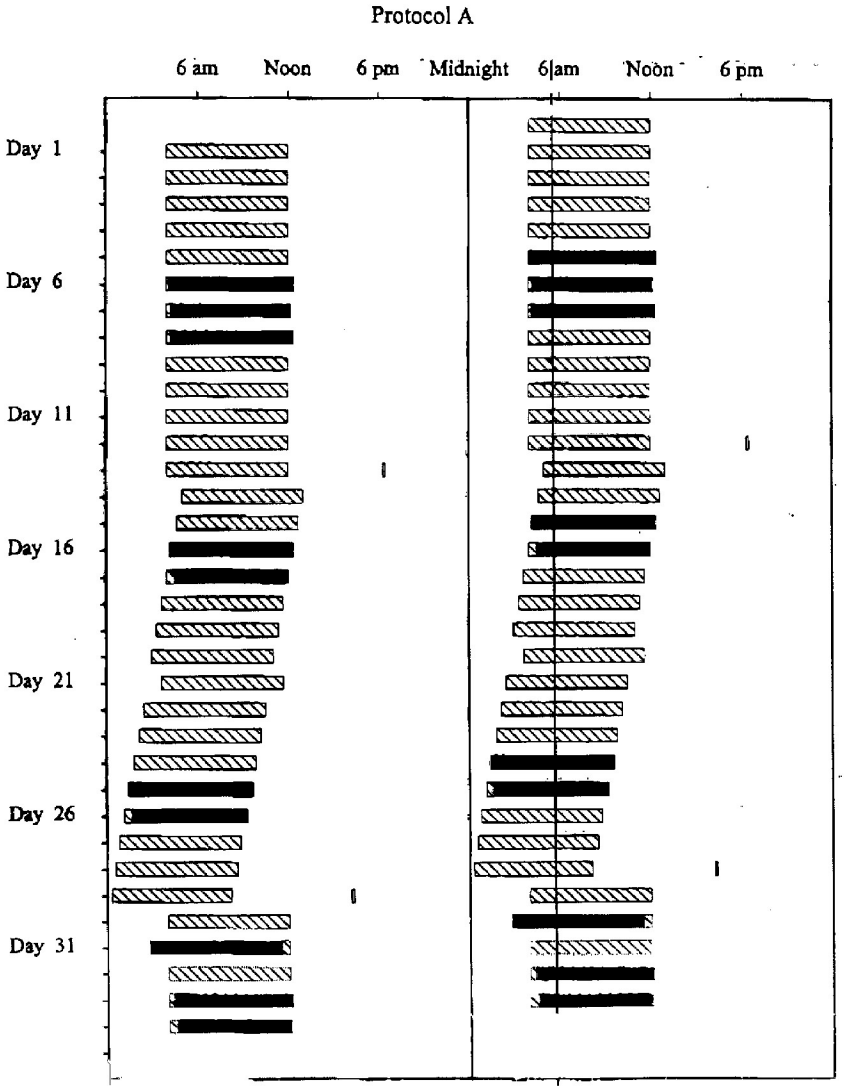


Figure 8. Mission data protocols.

The Neurolab investigation yielded 64 digital sleep recordings, 168 sleep logs or sleep diaries, 20 body core temperature monitoring sessions; continuous in-flight recording of light and Actigraphy, and 20 pre and post-flight Actigraphy sessions recording (Figure 9). The Neurolab phase of the investigation alone yielded 28 urine collection sessions. These samples were assayed for melatonin production and cortisol production. These hormonal profiles were combined with core body temperature to estimate the phase of the circadian clock.

I will not present the data in great detail, as at this point we are still blinded to drug treatment condition (Figure 10). We are in the process of combining the data for both missions. Once these data are analyzed,

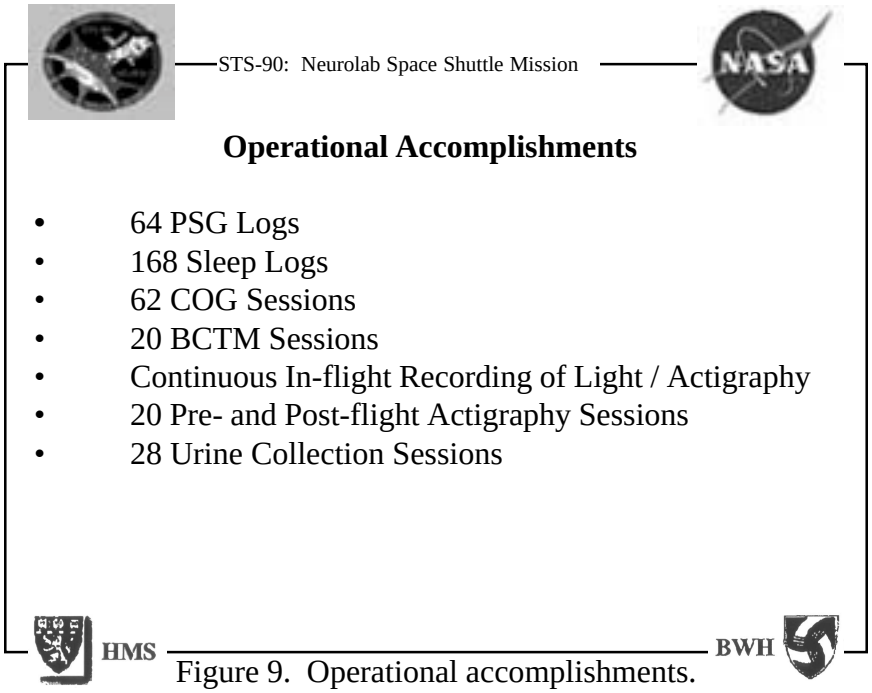


Figure 9. Operational accomplishments.

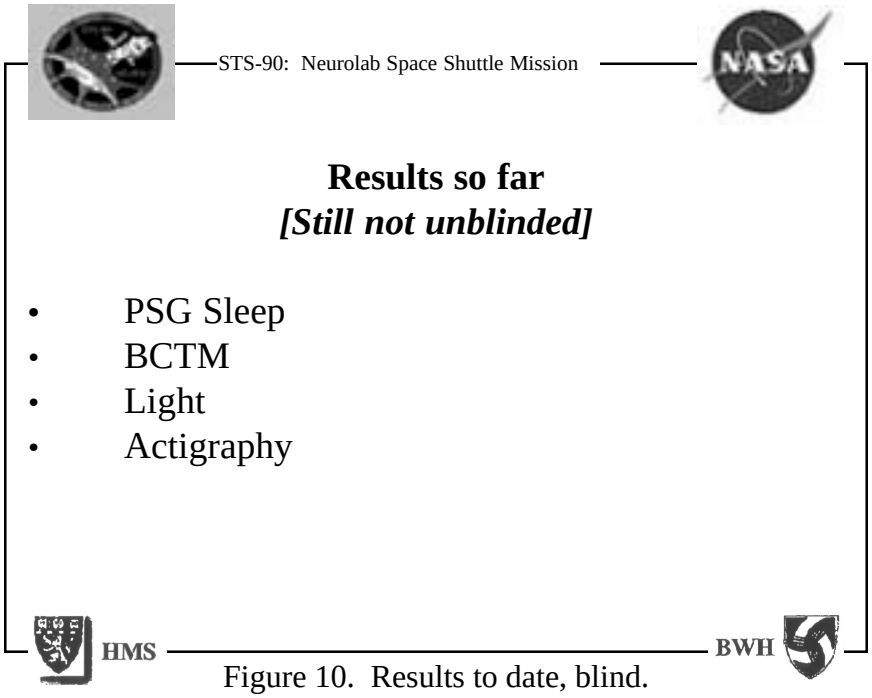
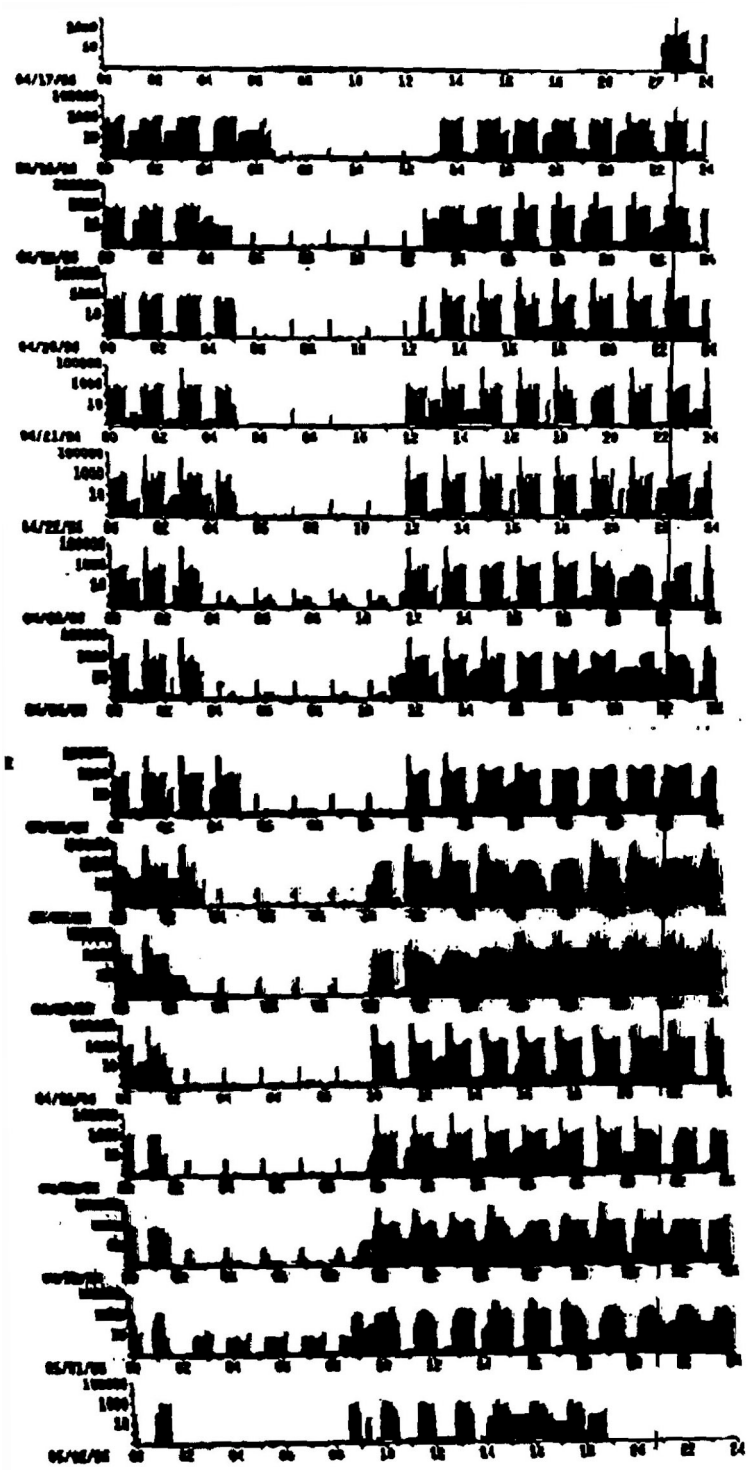


Figure 10. Results to date, blind.

we will unblind and either Dr. Dijk or Dr. Czeisler will be present the results at the April 14th [1999] Neurolab meeting.

The Actillume data revealed that the intensity of light to which crew members were exposed was highly variable within the space craft and across the day. The Actillume on the flight deck revealed a regular 90-

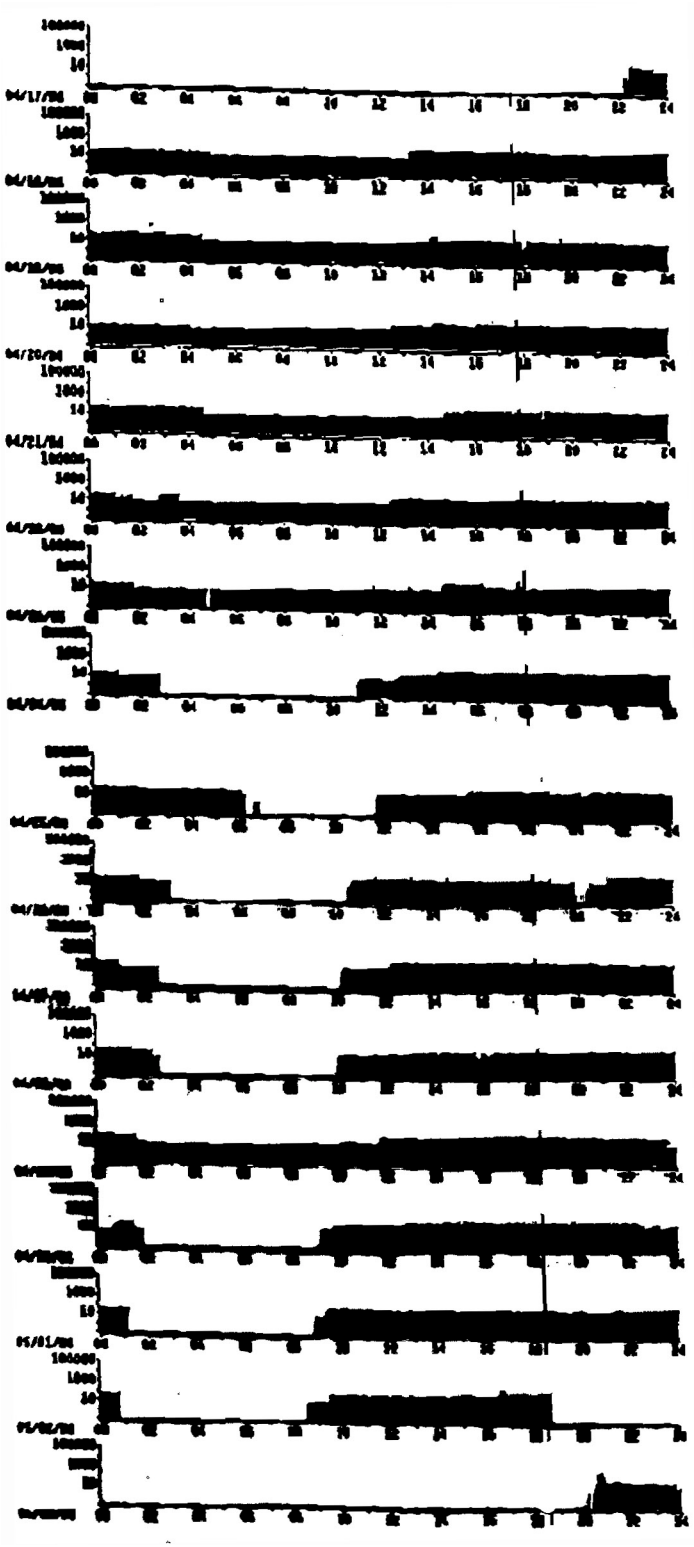
minute light-dark cycle associated with the orbit of the spacecraft around the Earth (Figure 11). The maximum light intensities in the Flight deck, during the 45-minute solar day, were certainly high enough to reset the timing of the circadian clock. Light intensities were much lower during the 45-minute solar night. During the astronaut's subjective night, light intensities remained very low, although the 90-minute light-



Flight Deck

Figure 11. Data from the flight-deck Actillume.

dark cycle is still present. The light intensities in the mid-deck, where crew members spend most of the personal time, were consistently very low. Similarly, the light intensities in the Spacelab were much lower than the flight deck and also did not fluctuate with the 90-minute orbit (Figure 12).



Spacelab

Figure 12. Data from the Spacelab Actillume.

Wrist Actigraphy data during the mission effectively distinguished between episodes of sleep and wakefulness (Figure 13). The approximate 20-minute advance of the sleep-wake cycle was most evident in the morning awakening. That is likely because wake time is determined by mission control. When the morning music from Houston began, the crew awakened and at least one responded to Houston. In contrast, bedtime or lights out time was set by the crew and to some extent by each individual crew member.

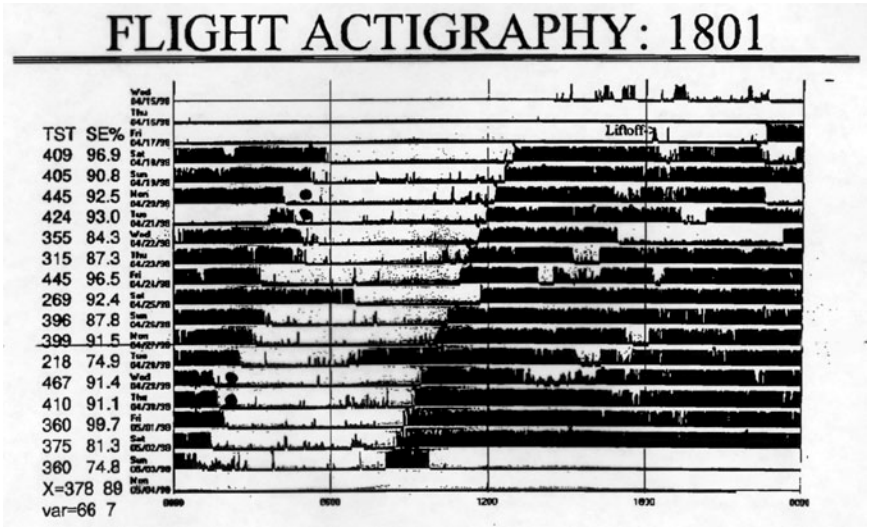


Figure 13. Data from the Actigraph.

In the Neurolab mission, bedtimes were much more variable than wake times, with variations associated with a delay of bedtime from scheduled bedtimes (Figure 14). Indeed, the Neurolab Actigraphy data demonstrate a reduction in total sleep in space. In these subjects at least, the reduced total sleep time was associated with a reduced time in bed or reduced time allocated for sleep, due to significant delays in bedtimes. This restricted sleep caused these subjects to experience cumulative partial sleep loss. Laboratory research done by Dr. Dinges suggests that this degree of sleep restriction for this many consecutive days can yield impairment of neurobehavioral functioning equal to or greater than one complete night of sleep deprivation.

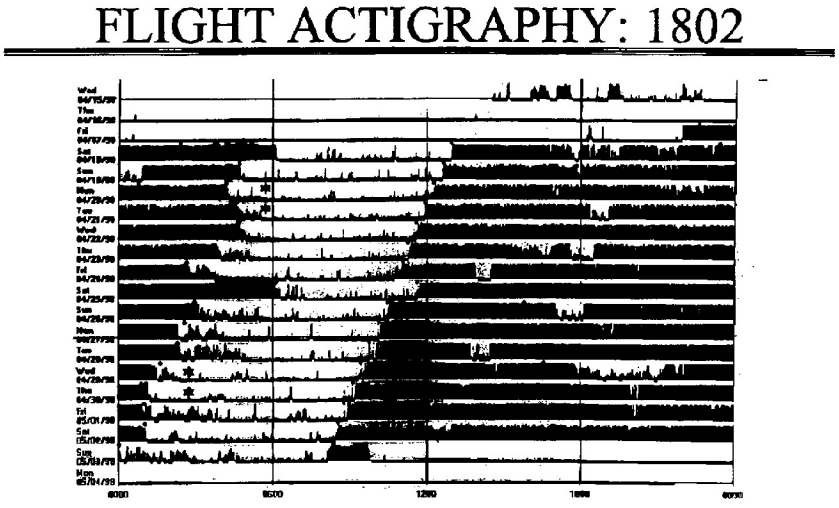


Figure 14. Flight data from the Actigraph.

This particular mission required a very compact work schedule that likely required "catch-up" time or preparation time during Pre-Sleep Activity (PSA), to accomplish all of the extensive mission requirements. Additionally, there were some acute mission concerns that demanded the attention of the crew during PSA time. In addition to mission demands, the delayed bedtimes may have been the result of the complex interaction between the two internal processes that promote sleep. If these subjects did not entrain to the near 23.6 hour day or if they were entrained at a different phase angle between bedtime and the circadian clock, then the bedtimes may have been scheduled to occur during what has been called the "wake maintenance zone." It is at this internal phase when the circadian system is maximally promoting wakefulness. Therefore, the delay in bedtime and subsequent restriction in sleep times may have been due to an interaction among mission requirements, self-selection of bedtime, and the phase relationship between scheduled bedtime and internal circadian phase. We are looking forward to providing greater detail on these and other results, including the effects of spaceflight on sleep quality and sleep structure, neurobehavioral alertness and performance, and circadian entrainment at the Neurolab Meeting to be held in this very room on April 14th, 1999.

Thank you very much.

Question and Answer

DR. SULZMAN: Thank you very much, Dr. Hughes. As he mentioned, he was drafted this afternoon to speak to us and really told a very nice story. We appreciate this very much.

Are there any questions that anyone would like to ask any of the speakers?

QUESTION: Have you noticed a difference in the atomic chain exchange between the life in microgravity in the form of gases, liquids, minerals, and solids as opposed to in gravity?

Also, is the atomic enthalpy or molecular enthalpy different? Does it vary in the micro-environment as compared to here on Earth?

Also, the positive and negative ionics, and that includes thought transmission, electrolytes and all that stuff, and the photonic frequency and photo period, how is that different in microgravity as opposed to here on Earth?

Thank you.

DR. SULZMAN: In the interest of time, let me try to answer that briefly, unless one of the speakers would like to.

There are a number of very interesting metabolic changes that occur in space. Much of this material, especially the electrolyte work, has been studied very carefully by Dr. Caroline Leach Huntoon, who happens to be with us today. This is all published and we will be happy to give you references for that.

With respect to the light frequencies that you talked about, I think you saw from the last speaker that there are very unusual lighting cycles that occur in different parts of the Shuttle, depending on whether or not they are exposed to sunlight from the 90-minute rotation or whether completely exposed to artificial lighting outside of the windows.

There are very interesting results that we have had in these areas. I'm afraid I don't have time to go more into detail on them. Thank you.

QUESTION: Just a simple question on the body core temperatures sensor. How often did they swallow it?

DR. HUGHES: There are individual differences in how long each sensor will remain in the digestive system. This depends upon individual differences in digestive processes and the time of day that this pill is swallowed. Typically, these sensors last between one day and three days on Earth and a little bit longer in space. Once the pill is lost, however, it can easily be replaced by taking another pill.

Mercury, Skylab, Spacelab, Spacehab, International Space Station: A Continuum
Dr. Charles Walker

Thank you all very much. Respecting the hour at which I have the podium, I want to reference you to the program where it says I'm a "Continuum Speaker;" do not interpret that as a "continuing speaker."

I want to take just a few minutes to ask us to reflect. Step back, step way back from the close-in observations and assessments that you've heard today and you will hear tomorrow and look at what we are talking about. We are talking about a program that is, in fact, science and research opportunity.

Let me reflect that we have come a long way. As this graphic attempts to illustrate, space, while it's a place, it's very fundamentally different (Figure 1). Fundamentally different, but in our accessing space for the purposes of the acquisition of knowledge, for testing theories, for learning, we do take human nature with us.

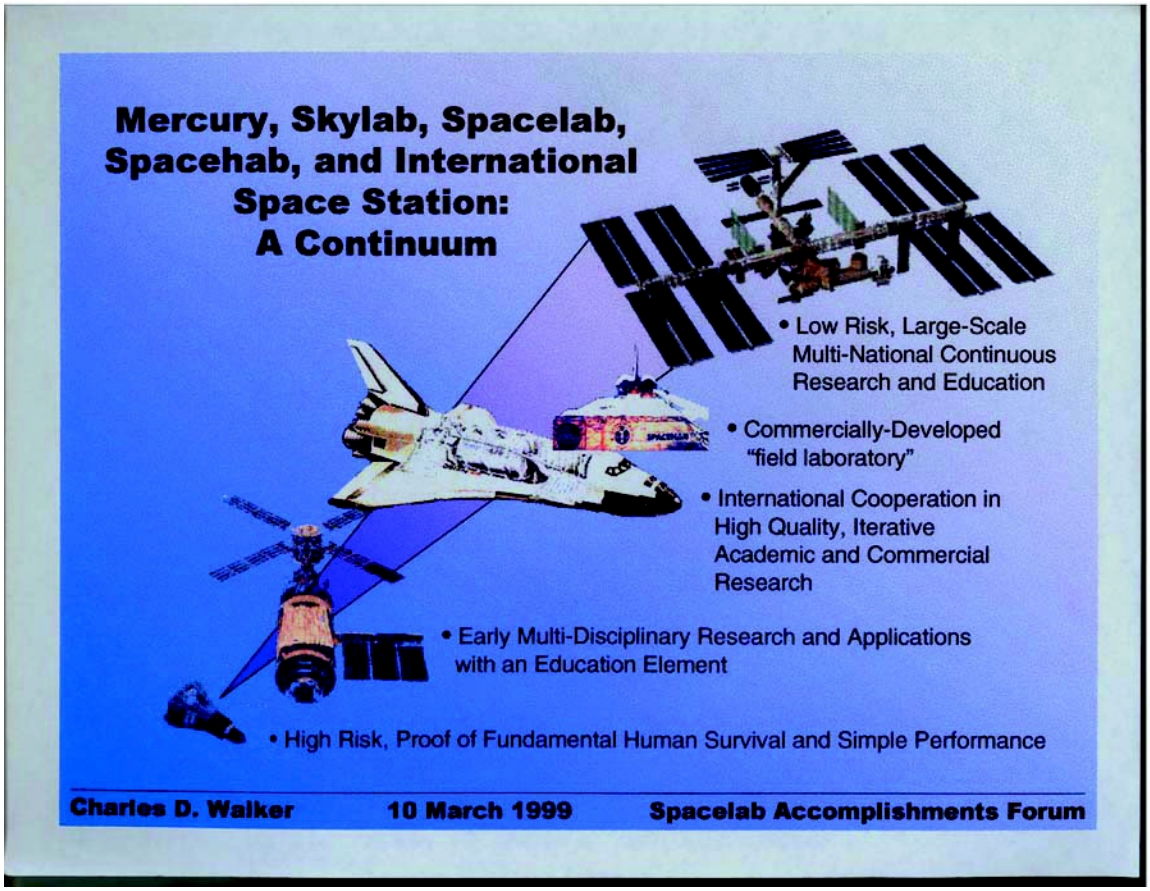


Figure 1. The continuum of space research.

Along this continuum we've taken and we have, in fact, manifested the human nature of both the basic acquisition of knowledge for knowledge sake, but we've also manifested our commercial needs. Our tendency is to want to apply what we know, and to bring back real products that we can use in our household and that we can market to our fellows here on Earth.

What I am talking about there is the following:

In 1958, we didn't know much about space. Larry [Young] did a very good job of relating what the Mercury program instigated in this country in 1959. Its goal was pretty basic: let's find out, number one, if that occupant of the Mercury capsule can survive in space, and let's also find out if, in fact, the equipment which we stuff him into will operate correctly and bring him back.

Now that's basic. We've moved well beyond there, thank goodness.

We have conducted real research in space. You are hearing that today. Virtually all that we conducted in the first decade and a half of the space age was government funded and basic research like the carrier vehicles we call satellites and Sputniki, but direct human interaction began with Project Mercury. It was very basic. That man was a pilot. That man was also an experimenter and an engineer, but in the most basic ways.

And that program was successful. The longest flight was 34 hours. There were six piloted missions. It ended in a mere four and three quarter years. After that, and really at the end of the program, we were well on our way to another goal. Not research per se; it was mission oriented; we had a political job to do. It was called the Apollo program.

When that program ended with success, we got back to research again. Skylab was using Apollo hardware, using Apollo systems in a manner that offered spacious accommodations for researchers, 300 investigations or slightly more, plus 19 high school student investigations. Education began to move into space. Solar physics, Earth resources, life sciences, and space technology were all investigated there.

Operational research as well was very important in the objectives of the Skylab program. It was an important step along the way, taking us from just intellectual inquiry about this new environment to one in which we actually have hands on — continuing hands on research.

Next along the way was the Space Shuttle, the Space Transportation System. There, as you've heard today, we began real international cooperation in the West, international cooperation in space with researchers having hands-on or next to hands-on opportunity to conduct material sciences, life sciences, observational research. It began with Skylab. It continued through Spacelab aboard the Space Shuttle.

Let me reflect here for just a moment on my personal experience. As NASA prepared for the first Spacelab pressure module flight I was an observer. I was watching because I was looking to learn to conduct my research in space. The opportunity that I was about to have, not aboard the Spacelab per se, but in the mid-deck of the Space Shuttle, was conducting biotechnical research aimed in a new direction different than the government sponsored, government funded research. This was commercially oriented research.

This continuum then began to, in fact, take a different bent. Let me talk briefly about that.

This different thrust has analogies, an analogy that I think is most directly demonstrated by the expendable launch vehicle business. Today, it's a commercial business. That technology began in exploiting purely government funded missiles. Before the mid-1980s it was just government contracted work.

Starting about the same time as the first Spacelab pressure module flight, companies began to roll additional units of expendable launch vehicles off their production lines, ran them through more streamlined, commercially oriented safety tests, evaluations of systems, and offered them to commercial payloads customers — communication satellites owner/operators.

A similar thing started happening in the early 1980s with space research. That has gone on to become what we call the SpaceHab. It's a module in the Space Shuttle payload bay like the Spacelab. It is designed for conducting not only research, comparatively simple research, but also operational activities important to our space programs. For instance it supported the Mir, that is the Phase I Space Station activity at the Mir Space Station.

During the period in time from the mid-80s until now, we have seen the tremendous success in accomplishing organized research that Spacelab has provided us. SpaceHab begins that separate track. Not government granted, or totally government supported, but with private capital at risk. A commercial investment that is providing augmenting capabilities to what our federal government supplies with the resources that NASA can provide.

From there, we look to Space Station. International Space Station is the bright star on the horizon. Spacelab has built a bridge to that star. The Space Station is a clear evolution from Spacelab, and we need to think of it that way. We need to look forward to the Space Station in that way.

Seventeen international partners and participants in this program are going to bring us an outfitted facility that will be unmatched in the history of our space programs. It will have capability for world-class research. It is going to be the centerpiece of our space research activities for the next two decades.

I urge you to look at it as an international research park. I urge you to think of it as a place to learn and to conduct research. Not only research and investigations in academic pursuits, but as a location for commercial research and development. That path now continues in this continuum. Commercial opportunity will be available at Space Station. Private capital, industrial firms, and even individuals can participate in the investigation of phenomena and technology in the unique realm of space.

Education will play an important role in the daily activities of astronauts, both hands-on as well as remote operations of activities aboard Space Station. Education is going to be stimulated by activities there. That is very important because as any number of speakers have said today already, as we look around this room, it is self-evident that our experience goes back more than a few years. The experience of Skylab and Spacelab and SpaceHab researchers won't go on that many more years.

There must be a next generation. There must be more investigators learning about human physiology, life sciences in general, materials sciences, learning about the universe beyond us through the observational sciences, as well as looking back at the Earth. The International Space Station will be a the place to

continue those investigations in a high quality fashion.

Before we go outside for the reception, I just want to mention that I think space research, as manifested in this continuum, is important not only for individual investigations as we have heard today, but in the greater whole of the human experience and the human pursuit to better our well being.

We are well along that path of pursuit. We are well along a continuum of which Spacelab was an important part. But we've got to encourage new activities on that continuum. Do your part. Encourage the future along this continuum. We've come a long way, but we've got a long way to go.

Thank you very much, and let's enjoy the evening.

International Participation In Spacelab Panel
Dr. Roger K. Crouch, Panel Moderator

I would like to welcome everyone this morning. I'm very honored to be a member of this panel. I've been friends with most of these guys for a long time; since about 1984 when I joined the International Microgravity Laboratory Science Working Group. This group was the coordinator for the science payloads on several of the earlier Spacelab missions. Without trying to steal their thunder, I want to introduce first Mr. Werner Riesselmann. He has a telecommunications degree from the Technical University of Berlin. He joined ERNO, Space Flight Technik in Bremen in 1970, and worked there for three years on European launchers, and for six years on the Spacelab development of electrical ground support equipment. He then moved into project management and worked on Spacelab-1 and the D-1 project as the manager for integration, test and operations of the European payloads. He joined ESA in 1986 at ESTEC and for ten years he worked on the hardware development and operations in the materials science and fluid physics area. In 1996 he became head of the Microgravity Payloads Division in the Directorate of Manned Space Flight.

The German representative here today is Dr. Horst Binnenbruck. He received his doctorate in physics in 1973 from the University of Cologne, started his career in 1974 at the DLR in the German Aerospace Center at Porz Wahn, and worked there for a couple of years doing research before moving into management of Spacelab Utilization in 1976. From 1990 to 1997 he was head of the Microgravity Research and Life Sciences Divisions of the German Space Agency/ DARA. He is currently head of the Microgravity Research and Life Sciences projects with DLR. He has done active research associated with the Spacelab-1 materials science double rack, German Spacelab Mission D-1, and German Spacelab missions.

Most of the discussions we have had so far have dealt with cooperation between ESA and the European countries and the U.S. because we have been mostly talking about development, but in the science area we have also had cooperative programs with NASDA since the Spacelab-1 flight. Dr. Shunji Nagaoka is with us today to talk about the NASDA program. He's been the program scientist at NASDA in the Office of Space Utilization Systems and has been involved in the program since 1984. Previously he was a physiologist and a biophysics researcher. The project efforts that he has been involved with include being a principal investigator on IML-1 and Spacelab J. He was a project scientist on the IML-2 mission, the STS-84 mission, and on STS-90, the Neurolab. His specialty is radiation biology and gravitational biology and he's a board member of JASMA, JSSS and JSAEM.

First of all, I would like to thank NASA for the invitation to this outstanding forum. This gives DLR (the German Space Agency) the opportunity not only to present the German contributions to Spacelab missions but also to highlight some remarkable results with respect to science and technology.

When I talk about Spacelab missions I have to look back on our mission. There had been a lot of different flight opportunities, starting with drop towers and going to missions to the Russian Space Station Mir (Figure 1). But there is no question that Spacelab missions have served as the most valuable "footprints" on our way to the upcoming utilization of the International Space Station.

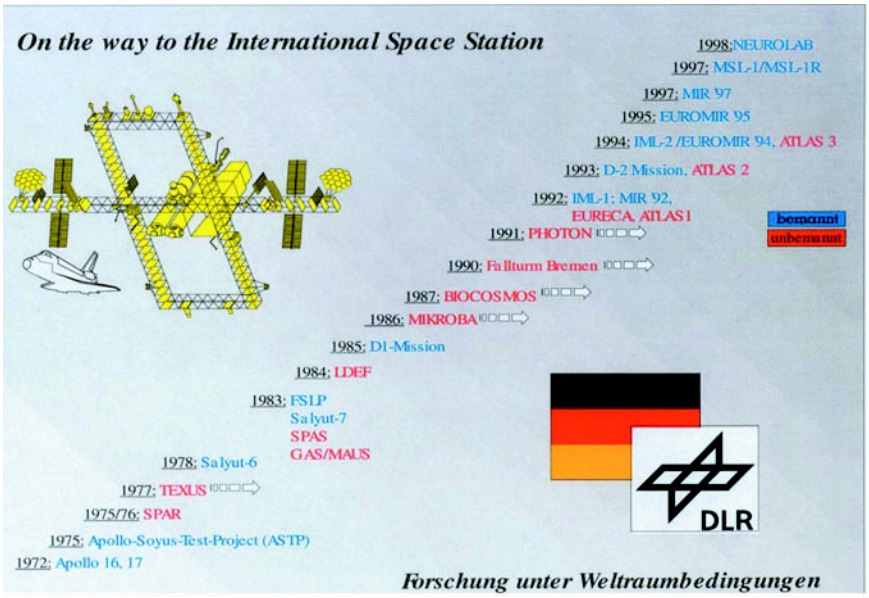


Figure 1. Summary of Germany's space activities.

As you all know Spacelab utilization is in principle multidisciplinary; this was also the case for the German activities, but nevertheless the scientific focus has been on microgravity research and life sciences.

From the very beginning, starting with Spacelab 1 (December 1983), Germany has made essential provisions for utilization payloads; it is worthwhile to mention here the Materials Science Double Rack, a highly integrated laboratory for performing materials science experiments in space. The Materials Science Double Rack (MSDR), in German called "Werkstofflabor" (Figure 2), had been successfully reflown twice after SL-1 in the two German Spacelab-missions, D-1 (October 1985) and D-2 (April 1993).

The materials science double rack was a real multi-user and multi-purpose facility with contributions from France and Italy, a complex system controlled by a simple 32k ram computer. The MSDR can now be seen in the German Museum branch at Bonn. Another facility of SL-1 should be mentioned here: The "inte-

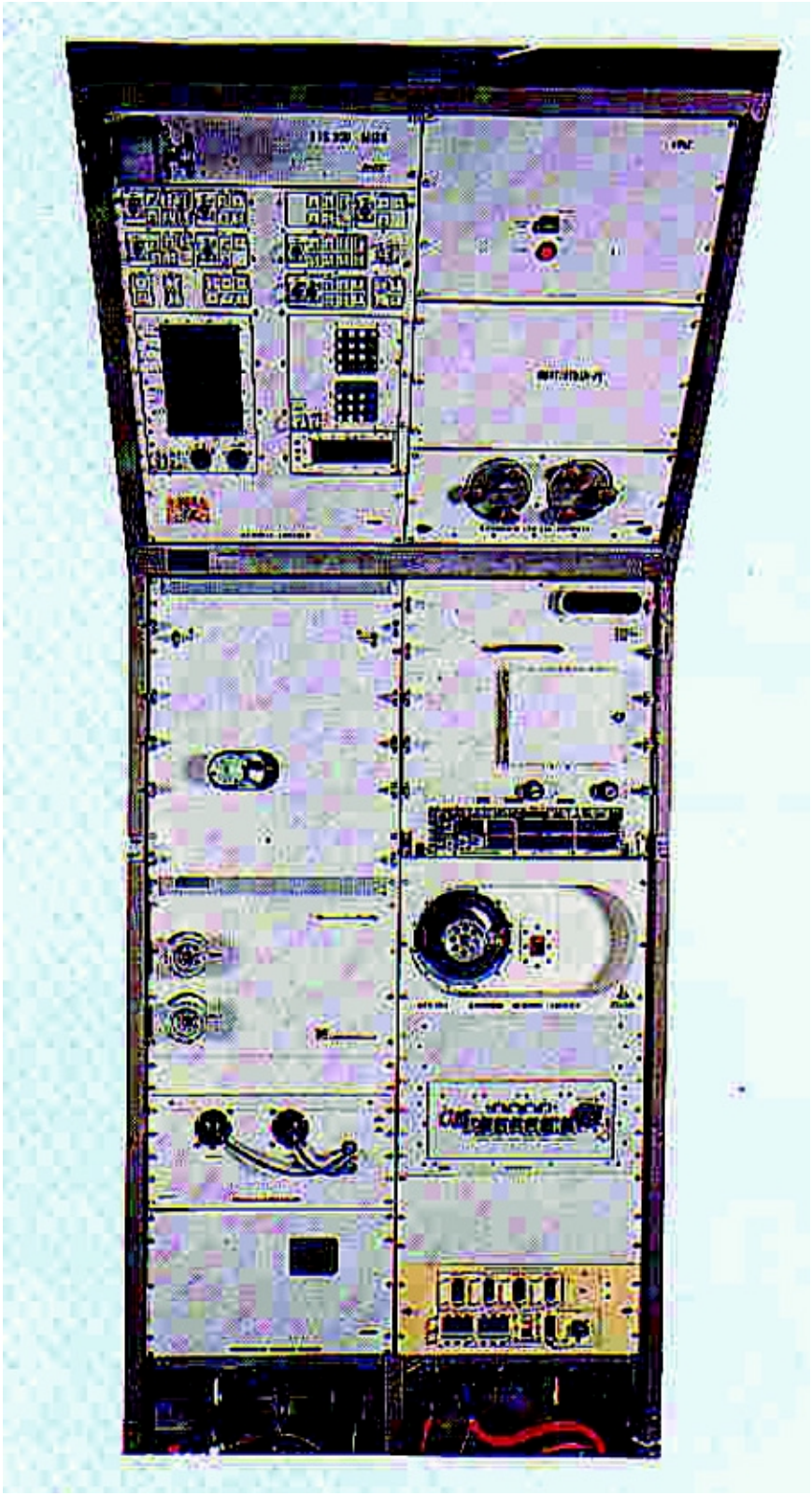


Figure 2. The Materials Science Double Rack (MSDR).

grated helmet" for vestibular research (Figure 3). This experimental equipment served for the study of the equilibrium (vestibular) organ of the inner ear by analyzing the reaction and movements of the eyes. A modern, advanced version of this facility is presently under development as a German contribution to the NASA Human Research Facility of the International Space Station.

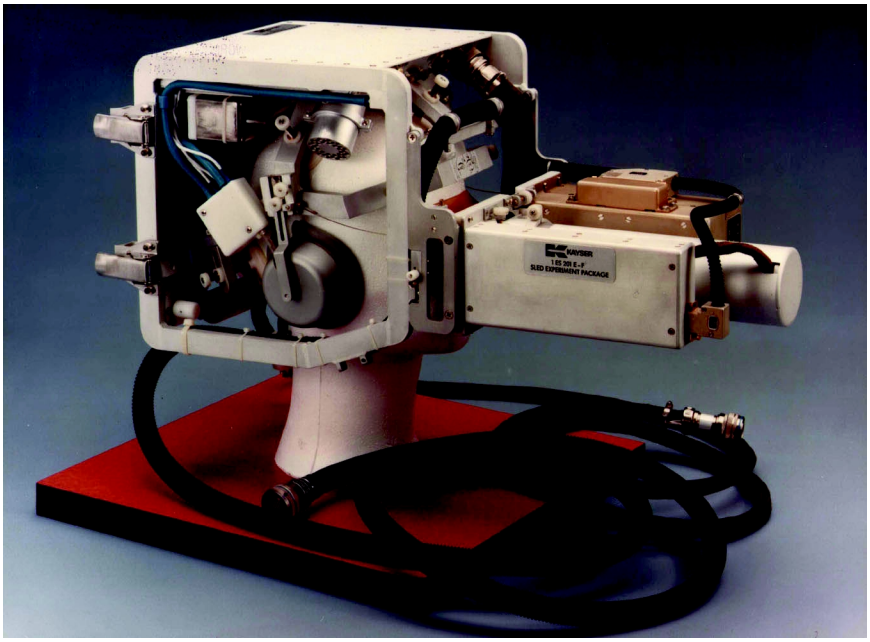


Figure 3. The "integrated helmet" for vestibular research.

The preparation and realization of the first German Spacelab-Mission, D-1, by the German Aerospace Center DLR (at that time DFVLR) had been a demanding task for us. The mission was primarily dedicated to "Microgravity Research and Life Sciences." Additionally, some experiments were performed in the field of navigation, one-way-distance measurements and clock synchronization.

After this, in every respect successful, mission DLR was well prepared for the next mission. Mission D-2 was originally planned as a D-1 reflight and scheduled for October 1988. Due to the Challenger catastrophe this launch date had to be shifted, finally, to 1993. This led to a comprehensive replanning of this mission resulting in a multidisciplinary one with reasonable participation of ESA, NASA and Japan. The experimental program comprised the research areas of materials science, life sciences, astronomy and Earth observation as well as automation and robotics. By using a Modular Optoelectronic Multispectral Scanner (MOMS) on this flight a three-dimensional mapping of selected areas of the Earth's surface could be developed and by switching to another operational mode diverse vegetation areas could be identified. Another highlight of this mission was the operation of the robot arm experiment, ROTEX, with the automatic capture of a free floating item. In this context the intensive application of telescience, specifically teleoperation, in this mission should be mentioned here.

Spacelab mission D-2 (Figure 4) was, for Germany, the most important milestone on the way to the utilization of the International Space Station. New experimental techniques had been developed, new procedures could be approved and an adequate ground infrastructure had been built up.

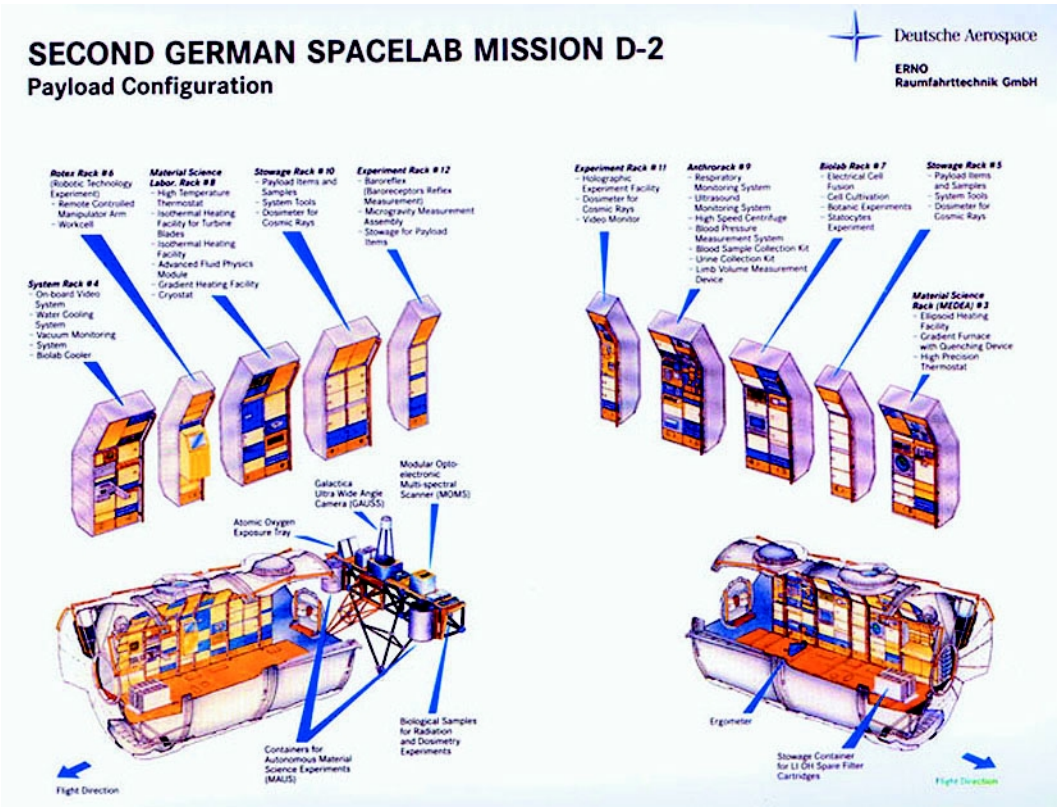


Figure 4. Payload configuration of the German Spacelab Mission D-2

Germany could also participate in the cooperative NASA International Microgravity Laboratory missions (IML-1, March 1992; IML-2, July 1994). On IML-2 an electromagnetic heating and positioning device (TEMPUS) was successfully flown for the first time. TEMPUS was developed by DASA/Dornier based on DLR plans. TEMPUS was reflown twice, on the NASA missions MSL-1 in April 1997, and MSL-1R in July 1997. The cooperative utilization of TEMPUS brought remarkable scientific results and opened up new perspectives for the Space Station utilization, for instance, measurement of industry relevant thermophysical properties.

In the field of remote sensing Germany had the opportunity to contribute to the ATLAS (Atmospheric Laboratory for Applications and Science) missions (ATLAS-1, March 1992, ATLAS-2, April 1993, ATLAS-3, November 1994) a Microwave-Atmospheric-Sounder (MAS). From the MAS measurements environmentally relevant data such as ozone altitude profiles could be derived.

In the last Spacelab mission, Neurolab, in 1998, German scientists had been selected to participate in some experiments in the field of neuroscience. Among the items DLR provided for this mission was a collapsible Lower Body Negative Pressure Device for cooperative usage. An advanced version is presently under development and will be delivered to NASA as a German contribution to the Human Research Facility in the course of this year. In addition, we had a small aquatic ecosystem (CEBAS) onboard this mission, a living quarters for fishes and snails, in which water plants produced the necessary oxygen. The system worked very well and can be used further in the study of gravitational biology for aquatic species.

This concludes the first part of my presentation: German contributions. But much more important is the question: What is the return of these Spacelab missions with respect to science and technology? Here are some examples.

Materials Science and Processing

Fundamental new findings have been made regarding:

- the phase separation kinetics of monotectic alloys resulting in the development of new Earth-bound pre-industrial methods for processing bearing metals.
- the formation of growth instabilities during the crystal growth process of electronic semiconductors
- the solidification front dynamics of alloys resulting in optimization of terrestrial casting processes. An improved aluminum casting process could be developed for processing certain parts of a spaceframe of an aluminum-made body of a car and for parts of a well-known European airplane.

These examples prove that space experiments can improve, and have improved, technical processes on Earth.

Precise knowledge of thermo-physical properties is of high interest for

- the validation of theoretical models - science relevant.
- modeling industrial processes - technology relevant.

Spacelab experiments could contribute to this field by:

- the high precise measurement of diffusion coefficients in metallic melts.
- the determination of thermo-physical properties in glass forming alloys.

Both results are basically not achievable under terrestrial conditions.

In the first Spacelab mission it was demonstrated by using model proteins that bigger protein crystals can be grown in space and, in certain cases, even better crystals for structural analysis purposes can be obtained. In the field of protein crystal growth in space remarkable results have been achieved.

Life Sciences

The medical research in space achieved a broad spectrum of results. Only two research areas, which are linked very closely to the Spacelab utilization, should be mentioned here:

- in neurophysiology/vestibular research new findings about the adaptation of the vestibular system to changed environmental conditions, such as weightlessness, resulted in new diagnostic methods in the case of disequilibrium malfunctions on Earth.
- new findings regarding the fine regulation of the cardiovascular system and fluid metabolism made possible improvements of diagnosis and therapy for the rehabilitation as well as the treatment of edema formation.

Development of new instruments for clinical diagnosis was initiated by Spacelab experiments, for instance:

- the self-application tonometer, currently available on the market, which measures intraocular pressure. It turns out to play an important role in treatment and prevention of glaucoma.

- the oedemometer, an instrument measuring tissue thickness in front and along the skin; today finds itself, in addition to the traditional applications in the medical area such as edema formation prevention for dialysis patients and pregnant women, in broad Earth-bound applications in monitoring of people working in extreme environments such as mountaineers and mining workers in the Chilean Andes.

Telemedicine

One remarkable spin-off of the D-2 mission led to a widely noticed cornerstone telemedicine project between DLR and the children's clinic at Köln-Porz. The diagnosis and care of high-risk babies suffering from Sudden Infant Death Syndrome received unexpected help from space. A D-2 space suit equipped with a set of sensors for transmission of vital medical data of astronauts down to Earth has been redesigned on the scale of rompers for infants. With the help of telemetry the little patient can stay at home while under permanent teleprotection from the clinic. In case of emergency the medical doctor immediately informs the parents and they will receive appropriate advice on how to react.

Automation and Robotics

The special requirements and conditions of a space flight have led to significant progress in the areas of "Automation and Robotics" and "Telescience and Teleoperation." Close cooperation between man and machine comprising different levels of robot autonomy was the basis of the success of the already mentioned ROTEX. It was clearly proven that a flexible configured robot system, quickly switching between different operational modes, would be a powerful tool in assisting man in space.

The progress achieved by the D-2 robotic experiment, ROTEX, has been transferred into a lot of different applications that are visible for the public today. An example is the development of an artificial muscle used as actuators for a new design of smart, multi-fingered robot hands or replacing the hydraulic actuators in airplane flaps and elevators.

Another example is the "Space Mouse," a sensor-based 6 degree-of-freedom manipulator for 3D computer graphics, which is also usable as a conventional computer mouse. Eventually surgical microscopes will be manipulated by that device.

This concludes DLR's Spacelab accomplishments with respect to Spacelab utilization. Not all goals could be reached, but nevertheless, remarkable results have been achieved proving Spacelab is an excellent space laboratory and revealing the scientific utilization potential of the International Space Station.

Last, but not least, I would like to thank NASA for the fruitful cooperation during the Spacelab era. I hope that this cooperation will be continued in the era of the International Space Station, that we will work together as we did in the past. Thank you very much.



Figure 1. Japan's participation in the Spacelab program.

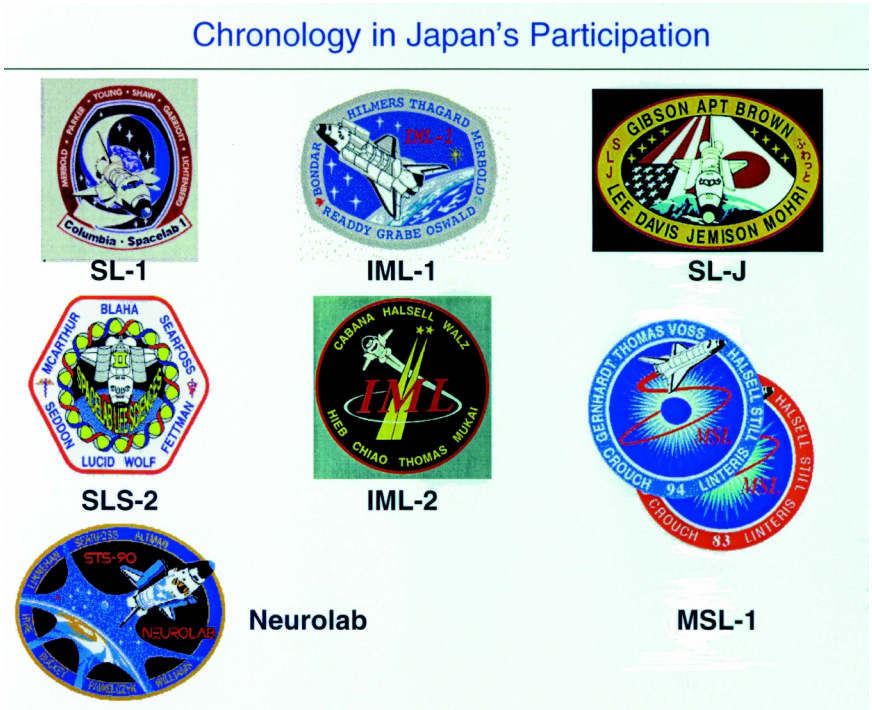


Figure 2. Mission chronology of Japan's participation in the Spacelab program.

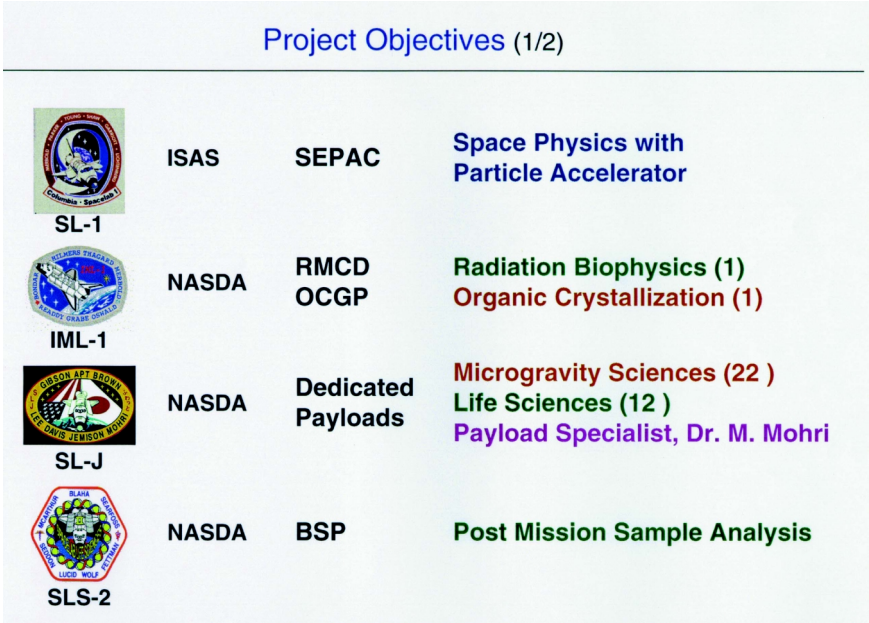


Figure 3. Project objectives part 1: SL-1, IML-1, SL-J, and SLS-2.

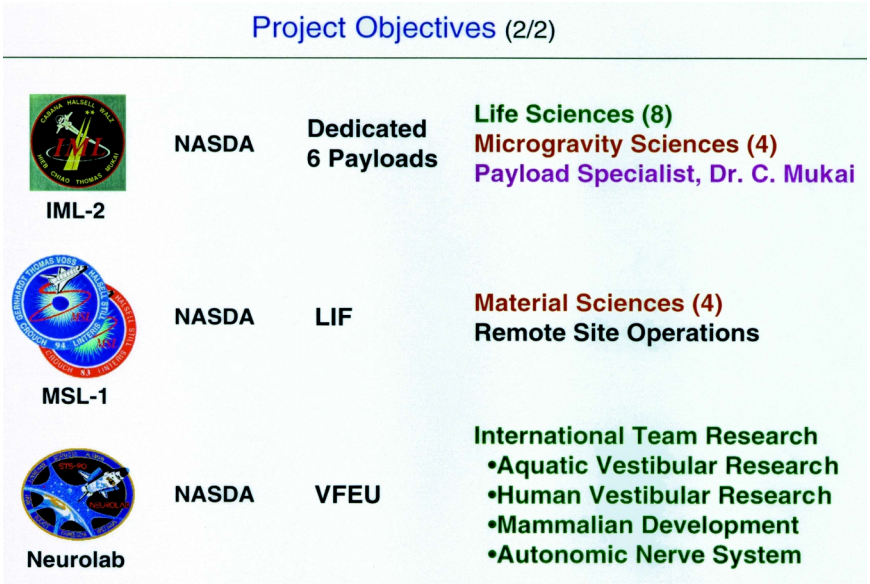
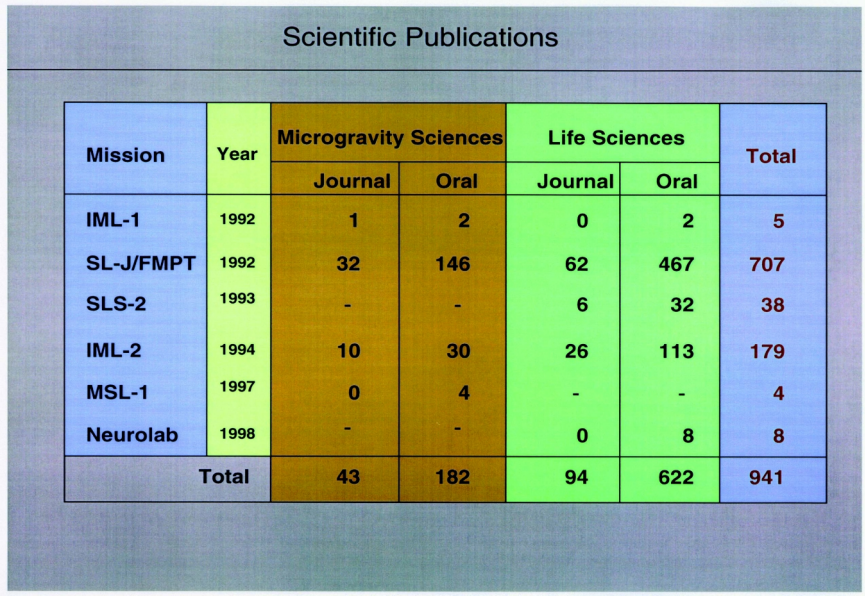


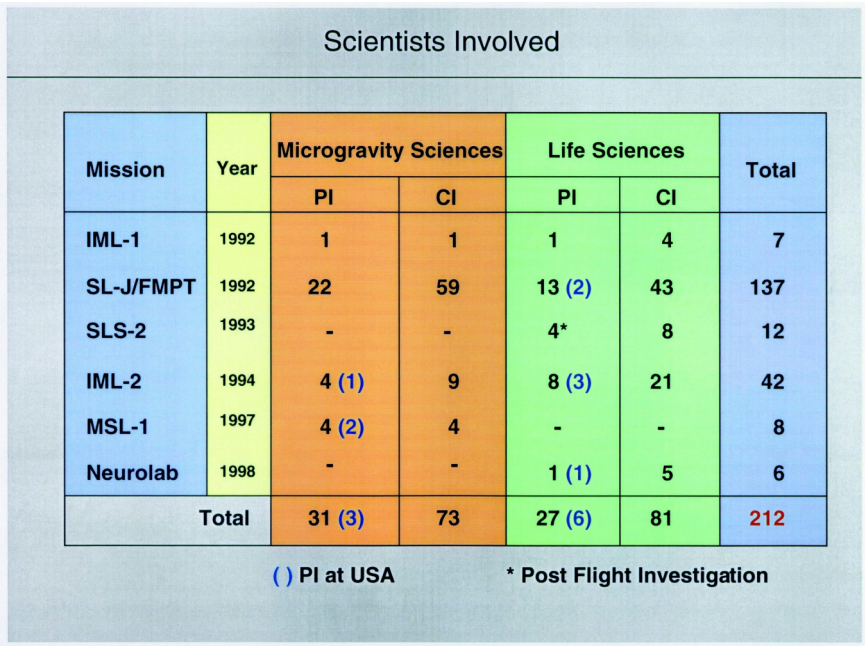
Figure 4. Project objectives part 2: IML-2, MSL-1, and Neurolab.



Scientific Publications

Mission	Year	Microgravity Sciences		Life Sciences		Total
		Journal	Oral	Journal	Oral	
IML-1	1992	1	2	0	2	5
SL-J/FMPT	1992	32	146	62	467	707
SLS-2	1993	-	-	6	32	38
IML-2	1994	10	30	26	113	179
MSL-1	1997	0	4	-	-	4
Neurolab	1998	-	-	0	8	8
Total		43	182	94	622	941

Figure 5. Publications resulting from mission science.



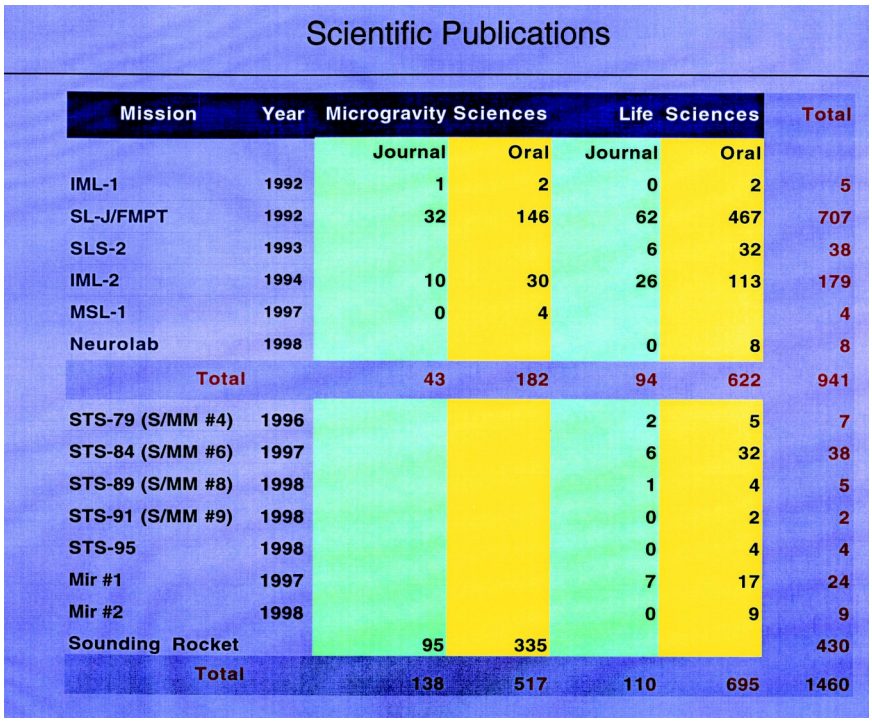
Scientists Involved

Mission	Year	Microgravity Sciences		Life Sciences		Total
		PI	CI	PI	CI	
IML-1	1992	1	1	1	4	7
SL-J/FMPT	1992	22	59	13 (2)	43	137
SLS-2	1993	-	-	4*	8	12
IML-2	1994	4 (1)	9	8 (3)	21	42
MSL-1	1997	4 (2)	4	-	-	8
Neurolab	1998	-	-	1 (1)	5	6
Total		31 (3)	73	27 (6)	81	212

() PI at USA

* Post Flight Investigation

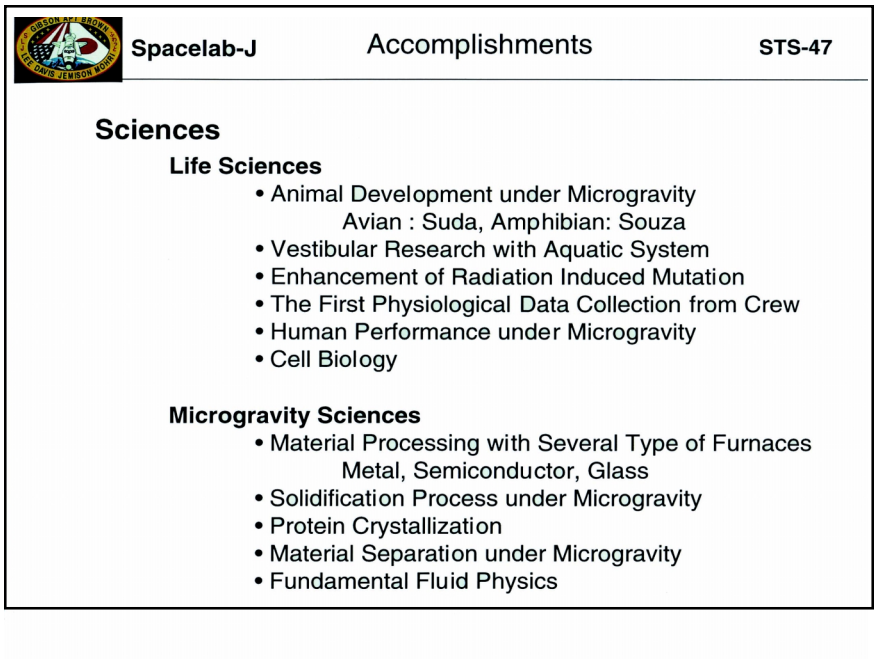
Figure 6. Personnel involvement in mission-related science.



Scientific Publications

Mission	Year	Microgravity Sciences		Life Sciences		Total
		Journal	Oral	Journal	Oral	
IML-1	1992	1	2	0	2	5
SL-J/FMPT	1992	32	146	62	467	707
SLS-2	1993			6	32	38
IML-2	1994	10	30	26	113	179
MSL-1	1997	0	4			4
Neurolab	1998			0	8	8
Total		43	182	94	622	941
STS-79 (S/MM #4)	1996			2	5	7
STS-84 (S/MM #6)	1997			6	32	38
STS-89 (S/MM #8)	1998			1	4	5
STS-91 (S/MM #9)	1998			0	2	2
STS-95	1998			0	4	4
Mir #1	1997			7	17	24
Mir #2	1998			0	9	9
Sounding Rocket		95	335			430
Total		138	517	110	695	1460

Figure 7. Publications from mission science by discipline.



Spacelab-J Accomplishments **STS-47**

Sciences

Life Sciences

- Animal Development under Microgravity
 Avian : Suda, Amphibian: Souza
- Vestibular Research with Aquatic System
- Enhancement of Radiation Induced Mutation
- The First Physiological Data Collection from Crew
- Human Performance under Microgravity
- Cell Biology

Microgravity Sciences

- Material Processing with Several Type of Furnaces
 Metal, Semiconductor, Glass
- Solidification Process under Microgravity
- Protein Crystallization
- Material Separation under Microgravity
- Fundamental Fluid Physics

Figure 8. Accomplishments during STS-47 (Spacelab J) by science disciplines.

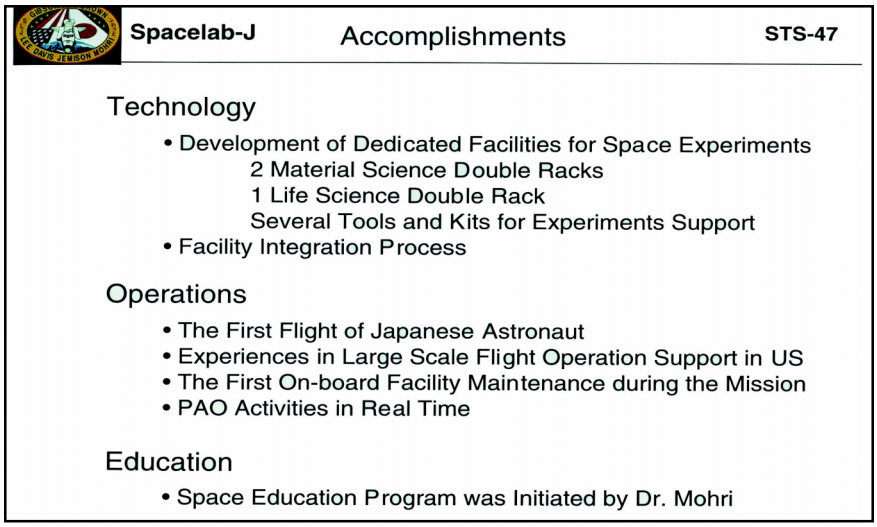


Figure 9. Accomplishments from STS-47 (Spacelab J) in technology, operations, and education.

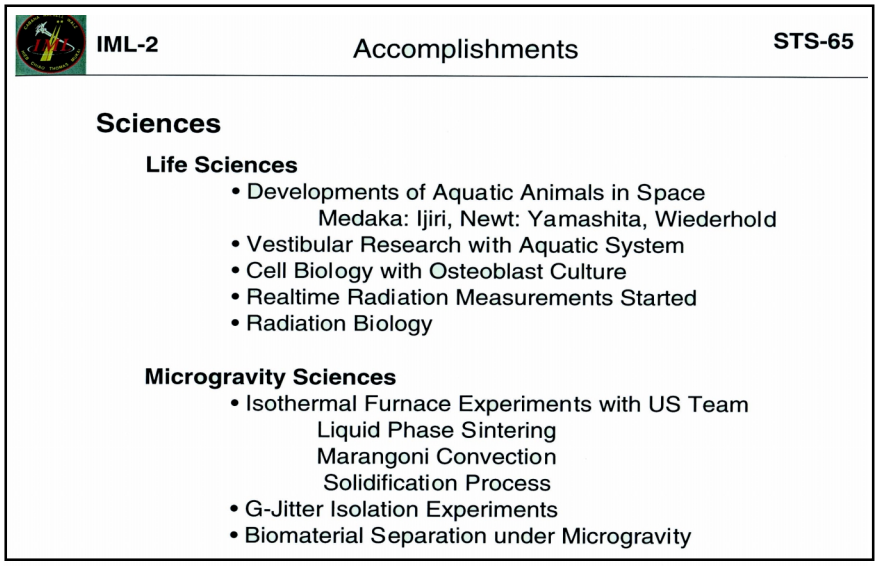


Figure 10. Accomplishments from STS-65 (IML-1) in the science disciplines.

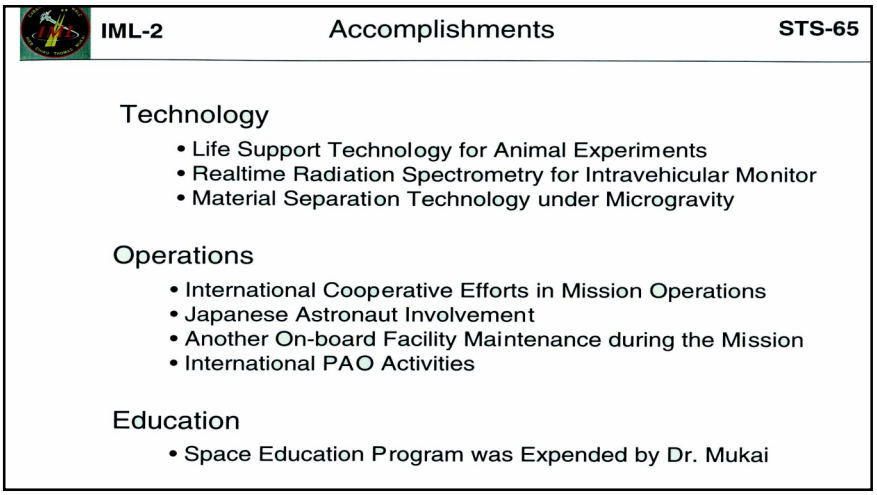


Figure 11. Accomplishments of STS-65 (IML-2) in technology, operations, and education.

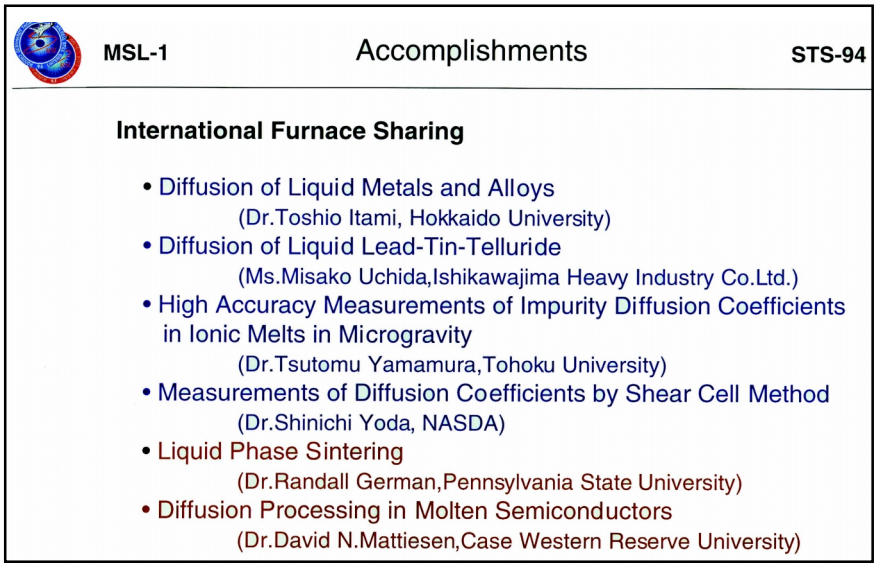


Figure 12. Accomplishments during STS-94 (MSL-1).

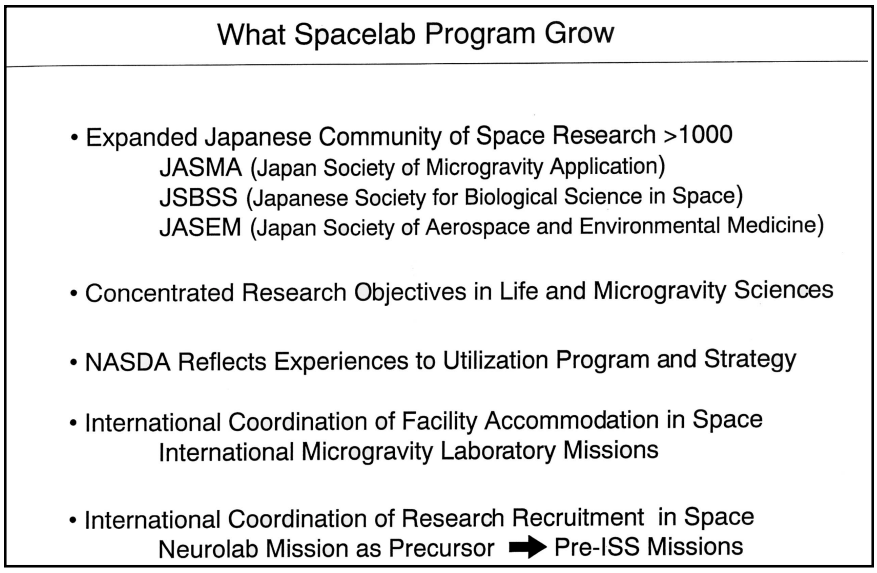


Figure 13. Spacelab's effect on Japanese space research.

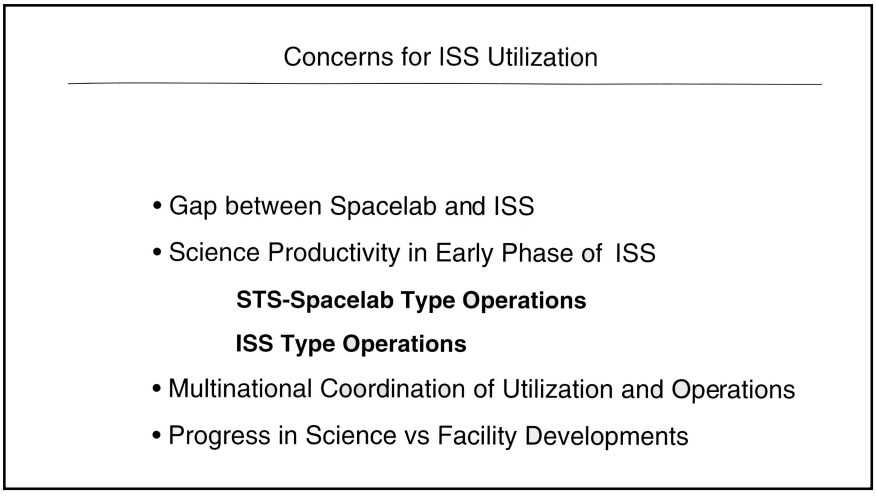


Figure 14. Concerns for optimal use of the International Space Station by Japan.

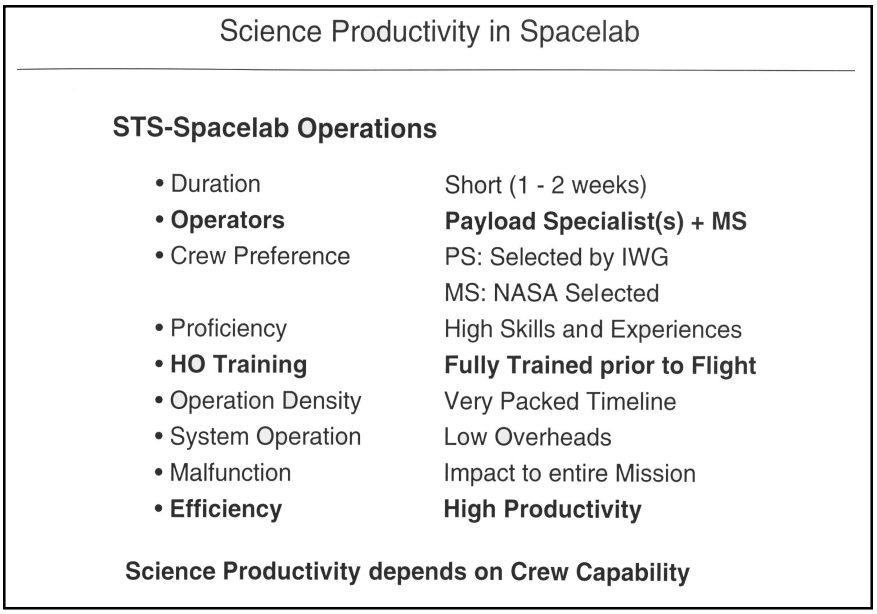


Figure 15. Science productivity requirements on Spacelab.

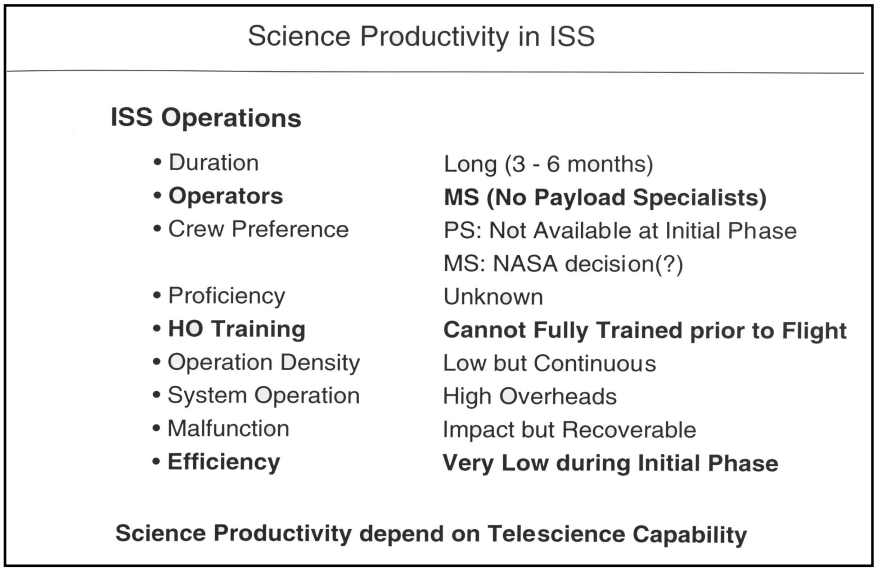


Figure 16. Science productivity requirements on International Space Station.

Mr. Werner Riesselmann

I would like to give you an overview on the European Space Agency's (ESA) involvement in the Spacelab utilization from the first flight, Spacelab-1 in 1983, until the last flight, Neurolab in 1998. Before doing so, I want to tell you about five essential achievements that resulted for ESA from Spacelab.

First, ESA itself. In the early discussions (1972-1973) about Europe's participation in the post-Apollo program, it was decided to merge the two existing European space organizations, the European Launcher Development Organization, ELDO, and the European Space Research Organization, ESRO, into one organization, which then became the European Space Agency (ESA) in 1975. The reason for this was that the major space players in Europe at that time, the United Kingdom, Germany, and France, all had very specific fields of interest. For instance, Germany was very interested in manned space activities, that means in Spacelab, the United Kingdom was very interested in telecommunication satellites, and France was very interested in gaining European autonomy in launchers (which later became the Ariane). It was decided to combine European forces into one agency - ESA.

Second, the decision for the Spacelab development was Europe's step into manned space activities and the related utilization. ESA was heavily involved in 11 Spacelab missions from 1983 to 1998.

Third, at the time of the decision on Spacelab and at the time when the Announcement of Opportunities for the first Spacelab experiments were sent out, ESA had no utilization program. Therefore, in the course of the preparation of Spacelab-1 in 1982 ESA started its microgravity program. So, this was also a contribution of Spacelab; that ESA now has a strong microgravity program that to a great extent was devoted to utilization of Spacelab and is now aiming to the International Space Station (ISS).

Fourth, as a continuation of the development of carriers for microgravity and for other space disciplines ESA built the European Retrievable Carrier (EURECA). As mentioned yesterday by my colleague Alan Thirkettle, ESA developed this marvelous piece of hardware which was very successful in its first and only flight, but could not secure necessary funds for a re-flight. For microgravity research, the free flying EURECA would have been an ideal platform.

Fifth, in direct continuation of Spacelab and EURECA, we now have the Columbus program, ESA's contribution to the International Space Station.

Now to Spacelab-1. This mission (Figure 1), as described yesterday by other speakers, was multidisciplinary and multinational. Spacelab-1 was a shared mission between ESA and NASA. NASA provided 13 experiments for this mission, which included one Japanese experiment, and Europe provided 59 (Figure 2). I will explain a little later this large difference in numbers of experiments.

The 59 European experiments were, in general, provided by the member states of ESA, not by ESA itself, and came from 11 European states. They were coordinated by the ESA office of Spacelab Payload Integration and Coordination in Europe (SPICE), set up as a multi-agency organization. ESA had invited DLR



Figure 1. Spacelab-1 overview.



Figure 2. Spacelab-1 experiment breakdown.

(the German Space Agency), at that time DFVLR, and CNES (the French Space Agency), to join this organization. Thus, we had ESA staff, DLR staff, and CNES staff.

Now to the imbalance of the 13 NASA experiments versus 59 ESA experiments. Early on ESA adopted a policy to build multi-user facilities that would serve the needs of quite a number of users in a specific discipline. In the case of Spacelab-1, it was the Materials Science Double Rack (MSDR), which in this case was not even built by ESA but was a German contribution to the first Spacelab mission in which we could accommodate 26 materials science and seven fluid physics experiments. So 33 of the 59 ESA experiments could be processed sequentially and partly parallel in furnaces and other facilities in the MSDR.

It was mentioned several times yesterday that in the late 1970s we had parallel developments ongoing; Spacelab, the Shuttle, and the experiments for the first Spacelab mission. This, of course, led to certain frictions, to certain delays, to certain changes, and to certain extra costs in the program. But finally it all turned out well.

The memorandum of understanding as well as the intergovernmental agreement between the U.S. and the ESA member states called for the first Spacelab flight being jointly planned on a cooperative basis between ESA and NASA. This was interpreted, as was mentioned by Harry Craft yesterday, as equal sharing of mass, energy, and crew time, because in the early negotiations it turned out that these three resources would be the critical ones. This could be achieved, more or less, by sharing the number of racks in Spacelab and the pallet on a 50/50 basis. This led to a net mass of 1,400 kilograms for the European payload, and more or less equal by a few kilograms to the same amount of the U.S. payload. Energy was shared, more or less, on a 50/50 basis as well. The payload specialists (introduced at that time as useful operators for this type of laboratory) were an American, Byron Lichtenberg, and a European, Ulf Merbold for ESA.

On this first mission we wanted to prove everything, especially on the payload side, with regard to the multidisciplinary capabilities of Spacelab. Finally, we had a concoction of experiments from astronomy, solar and space plasma physics, atmospheric physics, Earth observation, life sciences, materials sciences, and fluid physics. This created quite a problem in time-lining this mission with respect to the pointing of Spacelab, to low microgravity disturbance versus complicated maneuvers to accomplish Earth observation, or to point to astronomical objects.

This multidisciplinary approach was later changed and then never used again. The later emphasis was on discipline-oriented flights like the ASTRO missions that were presented yesterday, and like the life sciences missions. In the International Microgravity Laboratory (IML) we often had a mixture of materials science, fluid physics and life sciences experiments. This worked well together for the most part.

Because of the multidisciplinary payload complement of Spacelab-1, we had quite a number of constraints with respect to what would be the good orbital parameters for this mission (Figure 3). At first it was decided to fly 57 degrees inclination. On one hand this covered most of the Earth's surface for Earth observation experiments, and on the other hand it enabled Spacelab to be easily observed from northern Europe. Fifty-seven degrees inclination is, more or less, the northern tip of Scotland. At the time of the Spacelab-1 flight we had clear winter nights, and friends told me that one could easily see the Shuttle with Spacelab flying over Europe. Quite a number of people could experience it.

For Earth observation, of course, you need good lighting conditions for the objects that you want to monitor. Therefore, it turned out that 11:00 hours Florida time would be the best launch time to achieve this, and for good deep space viewing we needed a launch within seven days of the new moon. Investigators wanted



Figure 3. Mission parameters.

a very dark sky, and this could only be achieved this way. That then led, after a number of earlier delays, to the ideal launch date, which was set to be the 30th of September. For a number of reasons, indicated yesterday by Alan Thirkettle, it had to be delayed again. At the last moment we had a move to the 28th of November 1983. This worked out well, we had one additional mission day more than planned because of lower power consumption than expected and a number of orbits more because of problems with the computer system of the Shuttle. Therefore the first mission of Spacelab was, at that time, a record mission for the Shuttle. It was ten days, seven hours and 47 minutes.

After Spacelab-1, ESA tried to find the necessary funds for a number of Spacelab missions, but was unsuccessful; the Germans managed to have two dedicated missions, even Japan had a mission. ESA developed Spacelab but never could fly a Spacelab mission under the ESA flag (Figure 4).

In all the following Spacelab missions, from D-1 through D-2 (Figure 5), and then when luckily NASA introduced the International Microgravity Laboratory missions (IML-1, IML-2) (Figure 6), and with the Life and Microgravity Spacelab (LMS) mission, ESA could participate with quite a number of payloads (Figure 7). These payloads ranged from life science through protein crystallization, materials science in furnaces, to bubbles, drops and particles in a complex rack. Most of this equipment could fly two or three times on Spacelab missions. The Biorack, for instance, flew six times, three times on Spacelab and thereafter three times on Spacehab, the successor of Spacelab.

All this gave quite a lot of results to ESA investigators. You heard yesterday the science panels talking about the results and I will not concentrate on that. Actually, we are trying to compile and make public the results in an ESA microgravity database. Anyone from the science side interested in getting access to



Figure 4. ESA mission participation overview, after SL-1.



Figure 5. NASA support for international missions.



Figure 6. ESA experiment participation after SL-1.



Figure 7. ESA recent Spacelab mission participation.

science results of ESA facilities can access this database. The web address is http://www.esrin.esa.it/htdocs/mgdb/mgdbhome.html (Figure 8).



Figure 8. Spacelab scientific results.

I want to show now how we try to get from Spacelab to the International Space Station. All the facilities that we have built for Spacelab and used, for instance the Advanced Gradient Heating Facility (AGHF), find continuation in our attempts which started about a year ago in the development of facilities for the International Space Station, specifically the Columbus Laboratory.

In Figure 9 you will find the AGHF and its successor the Materials Science Lab; you have the Fluid Physics Modules, Advanced Fluid Physics Modules; the Bubble, Drop and Particle Unit, all facilities that flew on Spacelab, now continuing with the Fluid Science Laboratory (Figure 9). This applies for Biorack versus Biolab, the Advanced Protein Crystallization Facility versus the Protein Crystallization Diagnostic Facility. The Anthrorack, a physiology research facility, is now followed by European Physiology Modules. The Torque Velocity Dynamometer is followed by the Muscle Atrophy Research and Exercise System. This is a contribution of ESA to NASA's Human Research Facility.

It's the end of an era. We can say Spacelab was really an era in space research. At such a moment, one thinks of those who contributed most and who should be mentioned in my acknowledgement. These are:

- The group of McDonnell Douglas, TRW and Grumman consultants which greatly helped us in Bremen to perform the first Spacelab studies, to prepare the winning proposal, to implement the Spacelab design and development project and was actively involved in the early development phase.

- In Mr. Berge's and Mr. Thirkettle's presentations you have seen the complicated Spacelab management structure with the many involved companies. I believe that for a while we had 36 co-contractors plus subcontractors involved in the Spacelab development. To manage this, we distributed the load on



Figure 9. The legacy and future of ESA's participation with Spacelab.

many shoulders and installed a Spacelab Board of Directors. This very much helped at the working level in the project, especially in smoothing problems at higher levels in the various companies.

- Michel Binier, the ESA director responsible for Spacelab development at critical times, and responsible for Spacelab utilization as well.

- At NASA Office of Life and Microgravity Sciences and Application (OLMSA) we had two people, Joan Vernikos and Bob Rhome, with whom ESA had very longstanding, intensive cooperation. They enabled ESA to fly so many payloads on international Spacelab missions.

- On the ESA side I have to mention Günther Seibert, whose name you have seen on the initial announcements of this forum. He retired a few months ago. For many years he was the motor for all ESA microgravity activities.

- From the science side, of course, we built Spacelab for the users, for the scientists, for the investigators. I single out one very dominant personality and very impressive fighter for the European interests of the investigators, that is Luigi Napolitano.

- From NASA's side, from Marshall Space Flight Center, I would like to mention one more person, and that is Dick Marmann. In many Spacelab flights Dick had the responsibility for Payload integration and operation, and we had extremely good working relations with him and his team. We convinced him that we would do decentralized operations out of Europe. NASA was very skeptical at the beginning about giving away responsibilities from the POCC in Huntsville and letting investigators in Europe command their experiments through the Internet or through direct telephone lines. On IML-2 it

was done only as an exception, but later on the LMS mission we had an empty POCC. The NASA payload was operated to a great extent out of Ames and Lewis, and the ESA payload from the investigators in Italy, France, Belgium and Germany.

- My general thanks, of course, are to all investigators that over the 15 years, from 1983 to 1998, made use of Spacelab, and I hope they obtained good results.

Question and Answer

DR. CARPENTER: I have a question for all the panelists, and that is about how their agencies saw the cooperation in the future of human space flight. Spacelab certainly marks the beginning for international cooperation in human space flight, but after the Station, NASA is attempting to build momentum for missions beyond low Earth orbit. I wonder how our panelists see their own agencies planning their preparation or readiness to take on that kind of next generation, past Space Station.

DR. BINNENBRUCK: I think what we learned from the Spacelab missions is the necessity of working together on an international basis, at least in the field of fundamental science. This also means that we should form international groups in order to make the best use of the mission opportunity. I think this is one point of cooperation. The other one is that we all should make use of the available facilities; facility sharing should be the key word here. There are some countries which have developed specialties and gained important experiences. This should be brought in to the benefit of the international scientific community. In this sense, I think we should cooperate.

QUESTION: In conducting experiments in molecular biology, molecular genetics, which is life science, we need equipment that can be utilized in the space laboratory. Obviously the equipment we are using on the ground cannot be used in the Spacelab directly. How long does it take to convert this kind of equipment to be usable in the Spacelab? Secondly, how would one know what kind of equipment is available in the Spacelab; are there lists of equipment, such as DNA sequencing apparatus for conducting a number of molecular biological techniques? It would be nice to know what kind of equipment is currently available and what needs to be developed in the future.

DR. CROUCH: I'll answer that one, and I'll cover this a little bit in the wrap-up. Both programs, microgravity science and life sciences, are now going to international NRAs, NASA Research Announcements. In those NASA Research Announcements there is a listing of the hardware that will be available during the increment that funding would be available from that NRA. As far as how long does it take to develop the technology to take something that is as big as that podium over there to something that you can put on Space Station, with a little bit of luck it could take five to ten years; without luck, you never get to do your experiments. That's really a hard question to answer without being specific.

QUESTION: My question is, with the hiatus that will occur between the Spacelab experiments and the Space Station, what are your plans for attracting young people into the program and sustaining them through this period, keeping the research alive?

DR. CROUCH: I think the answer to that may come from the science panels that talk this afternoon, but we will let Shunji [Nagaoka] answer now.

DR. NAGAOKA: I think this must be answered by NASA. As far as I know, you are the biggest owner. So, NASA must be more eager to find opportunities. In Japan we are trying to utilize as much as possible, but any resource available in space now is very limited until the Space Station assembly is finished. We are trying to distribute more grants to prepare well on the ground for the research community. That is what we can do now. And, also, to push the science research to be flown in space. We need more focused research

in the early phase of Space Station because of the limitation of resources and we also need to reduce the risk of the sciences.

DR. BINNENBRUCK: I also agree that this question can only be answered by NASA. On the other hand, if we require more flight opportunities, there is no question, we have to pay for it. Somebody has to pay for it. If money would be available, I think there would be no problem to make use of Spacehab. I think it's a problem of money. If we had the money, then we could fly. This we cannot answer here.

MR. RIESSELMANN: I can only support the answer of my colleague from the Japanese side that for a certain time we may have to concentrate more on the ground preparatory work. On the other hand, if the money would be there and, this is an appeal to the scientists, if there is enough pressure on NASA to make Shuttle flights available for such research facilities as Spacehab in the years before the Space Station is really operational, then one could use this for what we call 'gap filler missions.' In the meantime, we concentrate on ESA's side to have, now and then, Shuttle flights with the Spacehab and adapt our Spacelab facilities to some extent to Spacehab, use those, and what we do in addition is reactivate those activities where we have a certain degree of autonomy. That means enhance the ground research by parabolic flights and sounding rockets. Europe has had quite an outstanding sounding rocket flight program with three to four sounding rocket flights in the past, which have slowed down for money reasons now to one or two per year. We hope with the financial discussions going on that we will increase this again to four flights per year. So that gives us at least a certain chance to do something for the user community.

DR. CROUCH: I think the real issue is, as Shunji says, this has never been all peaches and cream; it won't be peaches and cream from here on out. There will be times, as now, when we have to hunker down and prepare for the opportunities that will come, so we can take advantage of it. We need to plan to be ready to react quickly.

Having said that, what I would like to do now is close this session by pointing out that in addition to the distinguished representatives that we have here, Canada and the French CNES agencies have always been partners in these Spacelab flights. Due to scheduling conflicts and priorities within their agencies, they were unable to be here today, but we've had bilateral science working groups in both major OLMSA disciplines since the early, or at least the middle, 1980s.

Mike Sander created the International Microgravity Laboratory series of missions by NASA to invite international partners to come aboard with their hardware and with their scientists, and I think that has left a great legacy as we bridge into the Space Station era. Each of the disciplines, as I said before, are in the process of issuing joint announcements for research opportunities. In the future those opportunities will be the selection process for the science that will be done on Station, and it will be a worldwide community of scientists that are involved. We have two planning groups, the IMSPG and ISLSWG, which are the microgravity and life sciences planning groups. All of the agencies here are members. In addition, Russia, Brazil and the Ukraine have been invited to join. Canada and France already are members.

In closing, as the Administrator said yesterday, the Spacelab is not really a monument and it shouldn't be made into a monument. It reminds me of when I was in college and I had an old car that was not real reliable, but I really learned a lot in that old car. I did a lot of things I didn't know were possible. I did a lot

of things that were kind of risky, but it turned out to teach me a lot, and I had a lot of good results and fun as a result of the opportunities afforded by utilization of that car.

After I got a job and started making enough money, I bought a more reliable car that allowed me to expand my horizons. But it still took planning and it still took a certain amount of risk taking to utilize these new capabilities. And so I say let's move forward internationally, particularly from the science community, and utilize this new car we are going to have on orbit before long by building on the wonderful things we learned from Spacelab missions. Thank you very much.

Commercial Research Panel
Mr. Joel K. Kearns, Panel Moderator

As manager of NASA's Space Product Development Program and Microgravity Research Program, both sponsored by the NASA Office of Life and Microgravity Sciences and Applications, it's a pleasure to facilitate the Commercial Research Panel today. Before I introduce our panel members, let me say a few words about industrial and commercial space center participation with NASA on laboratory research missions, including Spacelab.

NASA has encouraged U.S. corporate investment and participation in laboratory research in space since the first joint endeavor agreements (JEA) were conducted in 1978. These JEAs were to provide incentives to U.S. industry to use the new capability of the Space Shuttle for both their own interest and to implement NASA's charter to encourage commercial use of space. In 1985 the Centers for the Commercial Development of Space were formed as consortia between NASA, U.S. industry, and academia to encourage and facilitate this commercial use of space. Many of the centers focused on the unique attributes available in the Space Shuttle as a laboratory: the free-fall environment, hard vacuum, and the unique vantage point of low Earth orbit.

Commercial research (as opposed to simply commercial use of the Space Shuttle to deploy communication satellites) first occurred in the early 1980s when several concerns purchased reservations aboard getaway special canisters for their own non-government sponsored research. Many of the commercial space centers, industries that work with them, and industries that work through joint endeavor agreements utilized the getaway specials, the small Shuttle mid-deck lockers available on almost every Space Shuttle flight, and later the commercial mid-deck augmentation module that was made available by the NASA Office of Commercial Programs to conduct exploratory and sometimes focused research. Later, industry and the commercial space centers used the unique capabilities of the Spacelab when those unique capabilities were truly needed; either when a large laboratory facility was needed, or a focused discipline oriented or multidiscipline research mission, or the unique skills of a trained professional scientist astronaut were needed. On several of the Spacelab missions, scientist astronauts who came from commercial space centers were payload specialists.

I find in retrospect that the research conducted by the commercial entities on Spacelab and on the Shuttle, and even in the Russian Space Station Mir was quite challenging. Although much of it was exploratory research, the researchers sponsored by NASA had to not only meet NASA's goals to facilitate commercial use of space (justifying the transportation investment by the U.S. taxpayer) and conduct quite rigorous, defensible and logical studies to exploit those environments, but also had to meet both the short-term and the long-term goals of their industrial partners, many of which were quite focused on their own near-term problems that they wished to exploit those particular attributes of space to aid them in a resolution.

On today's panel we have four members who worked at or with commercial space centers for some years, many of them exploiting the unique capabilities of the Spacelab. To my far right is Dr. Louis Stodieck of the BioServe Space Technologies Commercial Space Center. To my immediate right is Dr. David Klaus, also of BioServe Space Technologies Commercial Space Center. To my immediate left is Dr. Albert Sacco, Jr. of the Center for Advanced Microgravity Materials Processing, Commercial Space Center. To my far left is Dr. Weija Zhou of the Wisconsin Center for Space Automation and Robotics.

Our first speaker is Dr. Stodieck who obtained his Ph.D. in 1985 from the University of Colorado at Boulder in aerospace engineering sciences with an emphasis on bioengineering. He accepted a position as associate director for technical affairs with BioServe Space Technologies Commercial Space Center in late 1987, and was also appointed as associate research professor at the University in 1995. Since that time he has been responsible for managing BioServe's flight programs on all of NASA's carriers, including development and operations of life sciences and microgravity payloads flown on the KC-135 parabolic aircraft, suborbital rockets, the Space Shuttle, Mir Space Station, and now is planning for the International Space Station; providing management for over 25 articles of research apparatus payloads successfully flown on 13 Space Shuttle missions and twice to the Russian Space Station Mir. He also concurrently conducts his own research and directs research being conducted by graduate and undergraduate students in such areas as physiological effects of microgravity and the applications of microgravity and biomaterials processing and biotechnology.

Our second speaker is Dr. David Klaus, also with BioServe Space Technologies Commercial Space Center. He began his career working at the NASA Kennedy Space Center in Florida on Space Shuttle life support systems engineering as well as at Vandenberg Air Force Base operations. Later he also worked at the Johnson Space Center on advanced space suit prototypes and Space Station EVA operations planning. During graduate school at the University of Colorado, Dr. Klaus joined BioServe Space Technologies as a research assistant. His role in BioServe's activities included development of payload operations procedures, crew training, and integration support for seven Space Shuttle missions. As part of his assignments he proposed and developed a new course at the university entitled "Introduction to Space Flight Sciences," and he continues to instruct this course there. He earned his Ph.D. in 1994 with his thesis involving characterizing the effects of space flight on microorganism growth. After earning his degree, he was a visiting scientist at the German Aerospace research establishment in Cologne as a Fulbright scholar and returned to the University of Colorado in 1995 as a research associate at BioServe responsible for managing Shuttle and Mir commercial applications during space flight. He has most recently been appointed assistant professor in the Aerospace Department at the University of Colorado in 1998.

Our third speaker is Dr. Weija Zhou of the Wisconsin Center for Space Automation and Robotics. The abbreviation is WCSAR. He earned his Ph.D. from the University of Wisconsin-Madison in 1992 and is an associate scientist and assistant director at the WCSAR Commercial Space Center which is located at the University of Wisconsin-Madison. From 1992 to 1994 he was chief engineer at WCSAR where he worked on research and development of the Astroculture research apparatus, a plant growth unit for conducting space-based plant experiments of interest to industry which will be flown on the Space Shuttle. Since 1995 he has been a payload developer at WCSAR where he is in charge of the development of the Astroculture flights, the advanced Astroculture follow-on apparatus, and the commercial plant biotechnology facility being developed for the International Space Station.

Our last speaker is Dr. Albert Sacco of Northeastern University, and director of the Center for Advanced Microgravity Materials Processing, Commercial Space Center. Dr. Sacco earned his Ph.D. at the Massachusetts Institute of Technology in 1977 in chemical engineering. He then spent 20 years on the faculty of the Worcester Polytechnic Institute, the last nine of those years as chairman of the Department of Chemical Engineering. He has over 120 publications, primarily in the areas of carbon filament initiation and growth, catalyst deactivation, and zeolite synthesis. In 1992 Dr. Sacco was alternate payload specialist for the first United States microgravity Spacelab mission and in 1995 he flew upon the Space Shuttle Columbia as payload specialist for the second United States microgravity Spacelab mission.

I would like to thank all the presenters on today's panel on commerce research.

I represent one of the Commercial Space Centers, of which there are quite a number around the country. We have a very different mission from the basic science results and accomplishments that you have been hearing about in the last day and a half, and I want to give you a flavor of our accomplishments as they have come from our experience and opportunities on past Spacelab missions. In particular, I'm going to talk about some of the early work that has led to some very interesting applications in plant research. Our particular center is based at the University of Colorado, but is partnered with the Division of Biology at Kansas State University (Figure 1).

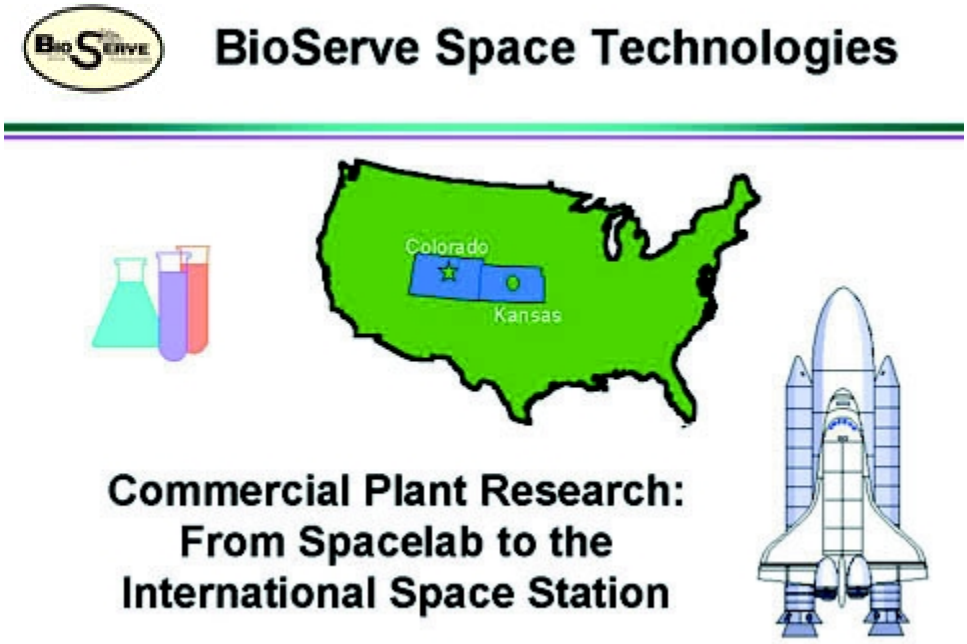


Figure 1. Introduction to BioServe Space Technologies.

As is true for all the commercial space centers and was just mentioned, our real mission is to bring industry into the space program; to educate them on the opportunities, to provide the necessary means for them to be able to use space and to explore the commercial benefits that might evolve from their participation in the program. Our goal is to help industries develop new or improve existing products, to improve their economic competitiveness, provide valuable benefits to the public, and so forth (Figure 2). One of the last bullets I have in Figure 2 I want to emphasize, because this has been brought up by a couple of speakers yesterday and today. Because we are at the University of Colorado, we have a very important mission: to try to train and educate the next generation of students that are coming into the program both from a science perspective as well as students that might become the next entrepreneurs and develop commercial opportunities in space.

Figure 3 gives you an idea of the flight experience our particular center has had over the years (Figure 3). We have, as Joel Kearns mentioned, flown on quite a large number of missions. I've highlighted in blue the

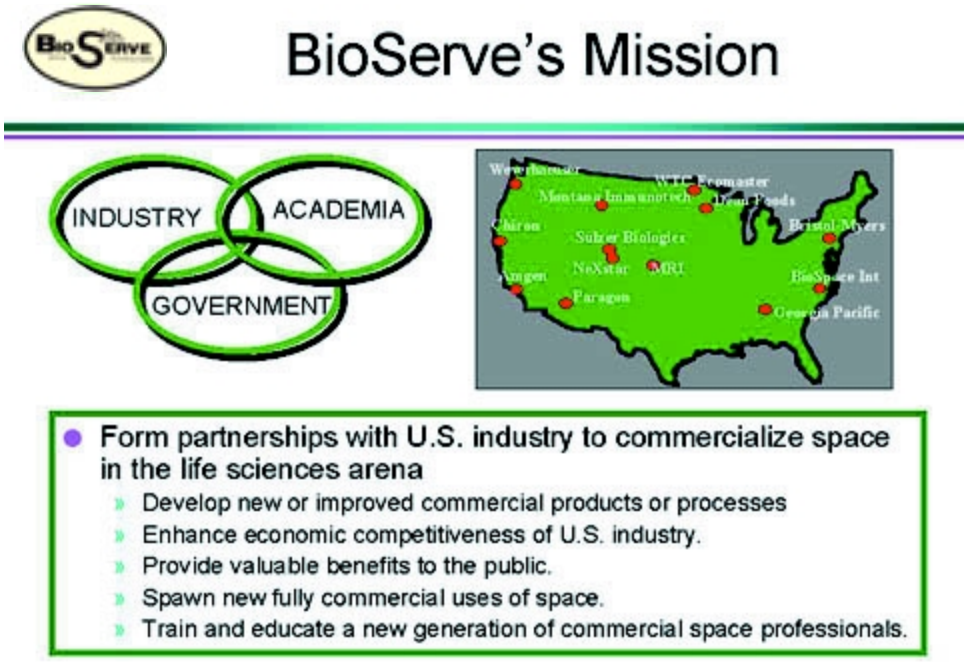


Figure 2. BioServe's mission.

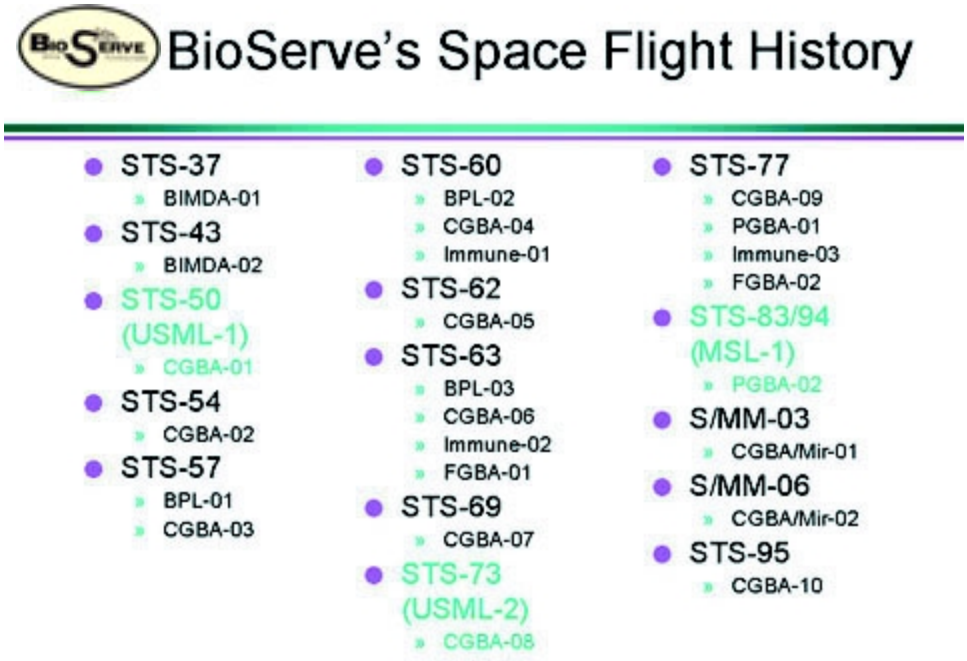


Figure 3. BioServe's flight history.

Spacelab missions that we have participated in, which included the first and second United States Microgravity Laboratory (USML-1 and USML-2) and the first Materials Science Laboratory (MSL-1).

I want to emphasize that the results that my colleague Dave Klaus and I will be talking about today span a number of missions, not just Spacelab. As a Commercial Space Center we have the need to be able to get into space as often as possible in order to really explore commercial opportunities and to get to companies flight data that will allow them to make investments and decisions that will allow commercial development to proceed.

STS-50, USML-1, was the first flight of the Commercial Generic Bioprocessing Apparatus (CGBA), which has become an absolute workhorse for us over the years. It has now flown a number of times including ten Shuttle missions and two missions to Mir. That particular payload truly is generic in that it was developed to support a wide variety of commercial life sciences investigations. On USML-1 and USML-2, in fact, the payload supported nearly two dozen separate investigations. So we are just going to be giving you a flavor of some of the results from those missions.

In terms of plant products and commercial opportunities, obviously it is not too hard to imagine that plants are a major part of our lives, something that we utterly take for granted in terms of food products, in terms of forest products, even pharmaceuticals (Figure 4). What I am going to do is talk primarily about results and the research that we are doing in the forest products arena, but also allude to the pharmaceutical area as well. Clearly, each of those three areas represent markets that are immense. It doesn't take too much imagination to realize that if there is any benefit that can be obtained from space to impact these, that could translate into millions of dollars in terms of economic benefit for the companies involved in these product lines.



Figure 4. Markets for plant products.

Why would we think that we might be able to gain some benefit from going to space? As you heard yesterday about the effects of space flight on human systems and animal systems, life sciences in general, plants also are affected by gravity. In fact, plants have been known for nearly 100 years to be gravitropic

(Figure 5). In other words, they have the ability to sense gravity and to orient themselves when they are first starting to grow seeds, germinating into seedlings, and so forth. There is certainly reason to believe that plants are going to be affected by going into space. In addition, plants, as they grow, and this is most graphically seen with trees, must be able to withstand the gravitational loads that are placed on them. This is not only the case with their own weight, but they must also be able to withstand weather conditions, whether that be snow loads or other kinds of adverse weather. They must be able to withstand those loads in order to continue to develop and be successful at generating seed. So, there is certainly reason to believe that going into a weightlessness environment will have an effect on plants. The question is whether those effects might be exploited from a commercial standpoint.

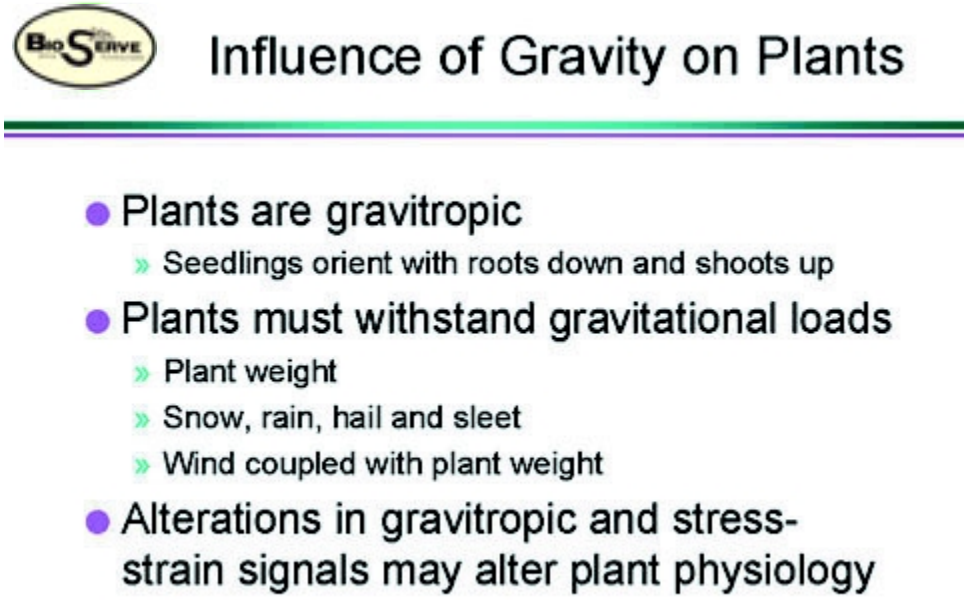


Figure 5. Influence of gravity on plants.

As I said, USML-1 represented the first flight of a payload we call the Commercial Generic Bioprocessing Apparatus and really our first major experience at developing hardware to be flown on the Shuttle. We developed a simple device that my colleague is going to talk about in somewhat greater detail called the fluids processing apparatus (FPA). It essentially is a glorified test tube that allows you to separate fluids or materials on the ground and then once on orbit mix them together to initiate an experiment, and then sometime later mix yet a third fluid into the first two to fix it or terminate it in such a way that you can bring it back. Thus, you can conduct a biological process exclusively on orbit and bring it back for analysis.

In the case of plant research, our early research was done in the FPA device in which we flew seeds (Figure 6). One of the constraints of the Spacelab mission was having to load some of our samples three to four months before the actual launch. Under such conditions, you can imagine most biological systems simply wouldn't survive the long storage period, but of course seeds are well adapted to long-term storage. So we did a number of investigations on seed germination and seedling development in which we would start with a substrate material containing the dried seeds. This figure [Figure 6] shows the devices after they had been activated in space. Prior to activation, there was another chamber that contained water or some type of an

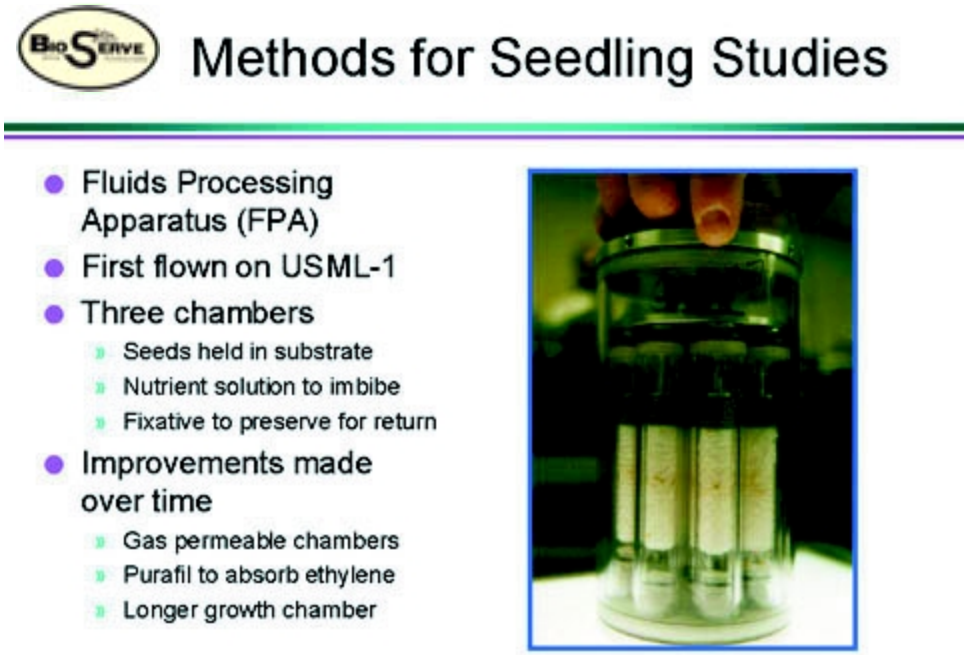


Figure 6. Methods of seedling study.

appropriate nutrient solution. In some cases, not shown here, there would be a fixative in a third chamber to preserve the seedlings after some period of growth in space.

Over time we have made improvements in this hardware in the case of seeds and seedling development, including gas permeable membranes so that we could provide good environments for the seedling development, materials to scrub ethylene, a compound which can affect plant growth and confound the effects of gravity, and some additional growth volume for the growing seedlings.

One of our graduate students who obtained his Ph.D. and has since gone on to NASA and is now a NASA young investigator did the work shown here (Figure 7). Dr. Jeff Smith, with seedlings grown on these earlier missions, studied the gravitropic response of plants and tried to understand the mechanism and characterize that mechanism more comprehensively. What you are looking at here are three-dimensional reconstructions that were done in collaboration with NASA Ames. The Biocomputations Group use their software to take serial sections of root material from these seedlings and geometrically reconstruct the internal organelles that are responsible for the gravitropic response. Amyloplasts, shown here in the yellow, are sedimented to the bottom of these cells in the one G situation. As you might expect from seedlings that are fixed on orbit and brought back, you see that they are not sedimented at the bottom but rather suspended here in the center. Further, using a simple device called the clinostat, which gives you a constantly changing orientation with regard to gravity, you also get suspended amyloplasts.

The paper on this work actually presented results that were very interesting from the standpoint that the amyloplasts in the zero G situation increased in size and increased in number, therefore increasing the fractional volume that they held in the cells that are responsible for the gravitropic response. The authors concluded that there was a feedback of gravity in controlling this part of the gravitropic system. In other

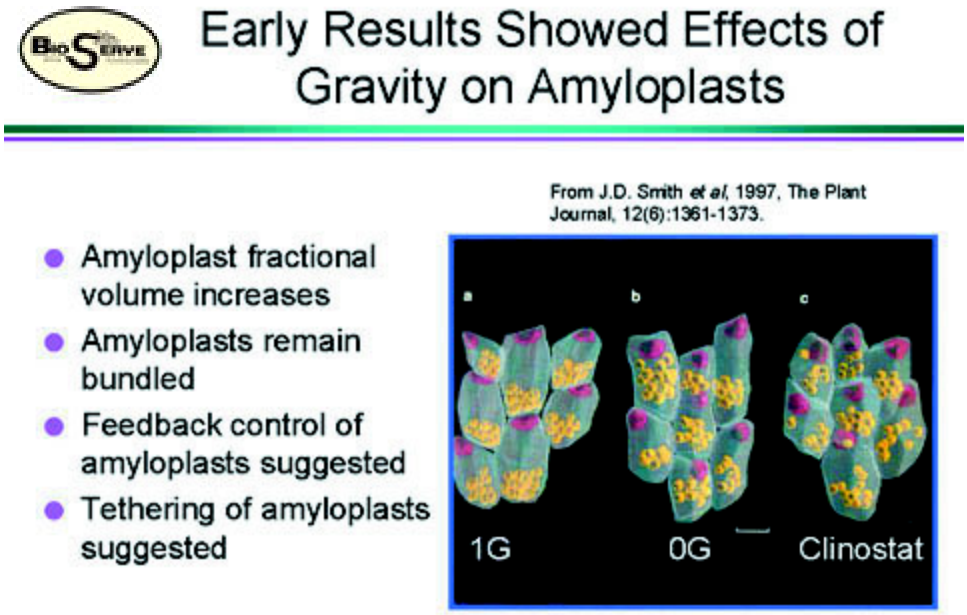


Figure 7. Effects of gravity on amyloplasts.

words, you might expect that without the gravity signal these organelles increased in size as a way of trying to turn up the gain and trying to find a gravity signal. This demonstrated for the first time that such a feedback system might exist and also showed that these organelles, despite low gravity, remained essentially clumped together. This result led to the suggestion that amyloplasts may in fact be tethered so that they respond as a single mass rather than as individual organelles. The question is, how does this relate to commercial research? In fact, we are very interested in the signaling mechanisms that affect the development of the plants and how they grow from seedlings to mature upright plants. There may be similar cells located in the upper parts of the plant, in the aerial tissues, that may influence how aerial tissues grow and develop in a gravitational field.

What I want to do now is talk about a commercial application specifically with regard to forest products. In this case, as I said earlier in the talk, the markets are in fact quite immense (Figure 8). The global demand for wood is on the order of 1.5 million cubic meters per year. From a paper and pulp standpoint, even a small improvement in the yield can result in millions of dollars per year in cost savings or cost advantage to a pulp manufacturer.

There is a lot of interest in the forestry industry to develop trees with a greater yield. For example, there would be a lot of interest in trying to grow trees in the tropics where they grow very quickly, where you can shorten the time from seedlings to mature trees. The problem is that the trees that are adapted to the tropics and grow well are not trees that are good for making pulp and ultimately paper. Pulp manufacturers want less of a structural compound called lignin. Lignin, as it turns out, is a material that is extremely difficult to remove from trees but must be removed in order to obtain pulp and create paper. Further because this material is very difficult to remove, the methods used impose significant challenges to the environment. On the other hand, with regard to energy and lumber uses, it is desirable to increase lignin content and



Figure 8. Market potential for forestry products.

make the wood more dense and therefore stronger. More dense wood also has a higher energy content. There is a lot of interest in developing new genetic strains, transgenic trees with improved properties. It would be ideal be able to tailor lignin content in trees to obtain the desired properties.

Lignin comes from phenylalanine through a very complex set of biosynthetic pathways that produce three subunits that are then eventually polymerized into lignin (Figure 9). Lignin plays three major roles in

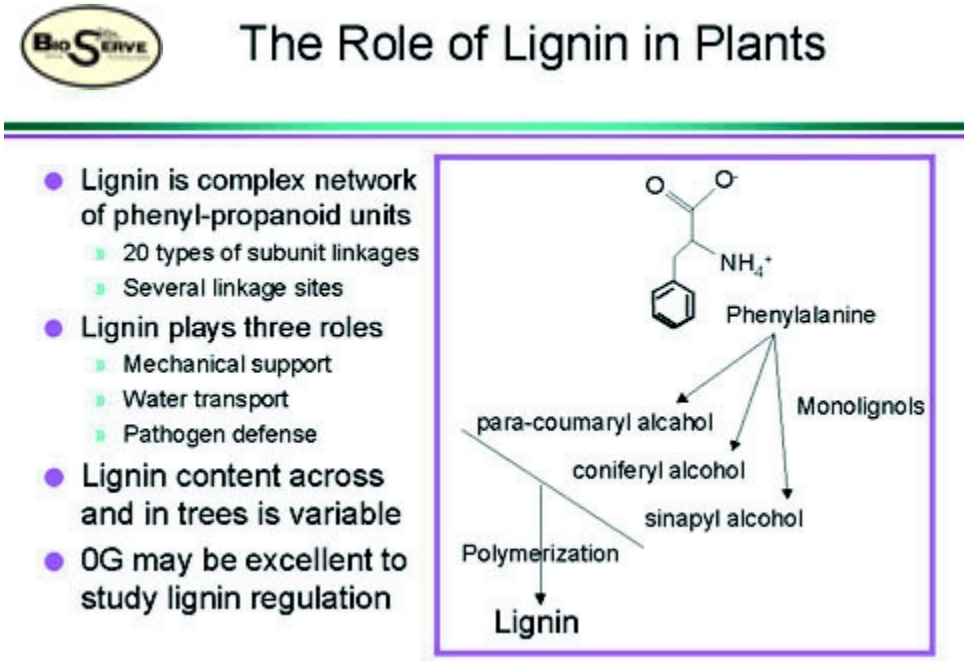


Figure 9. The role of lignin in plants.

plants. It provides mechanical support, which is what I've been emphasizing, but also is critical for water transport being a major component of the xylem, the vascular system of the trees, and it is also very important for pathogen defense. So when you think about it, if you are going to create a transgenic tree that might have less lignin, you want to be careful that you don't destroy some of the other important functions of lignin. Microgravity in fact, is probably an ideal environment to be able to study this process and to be able to dissociate the mechanical loading and the resulting lignin from lignin used in these other functions. Again, one of the early results from the USML-1 and USML-2 time frame was from a student that was looking at seedlings from alfalfa and looking at the vascular elements, the lignified cells that were present in these seedlings. What you see here with the yellow stain are some of these cells (Figure 10). What he found was that in space flight the number of lignified cells are reduced. In addition, the arrangement of these cells, here in a tetrarch arrangement versus a triarch arrangement from the flight, were quite different. Specifically, a triarch arrangement was typically found in zero G seedlings while a tetrarch arrangement was almost always found in the one G seedlings.

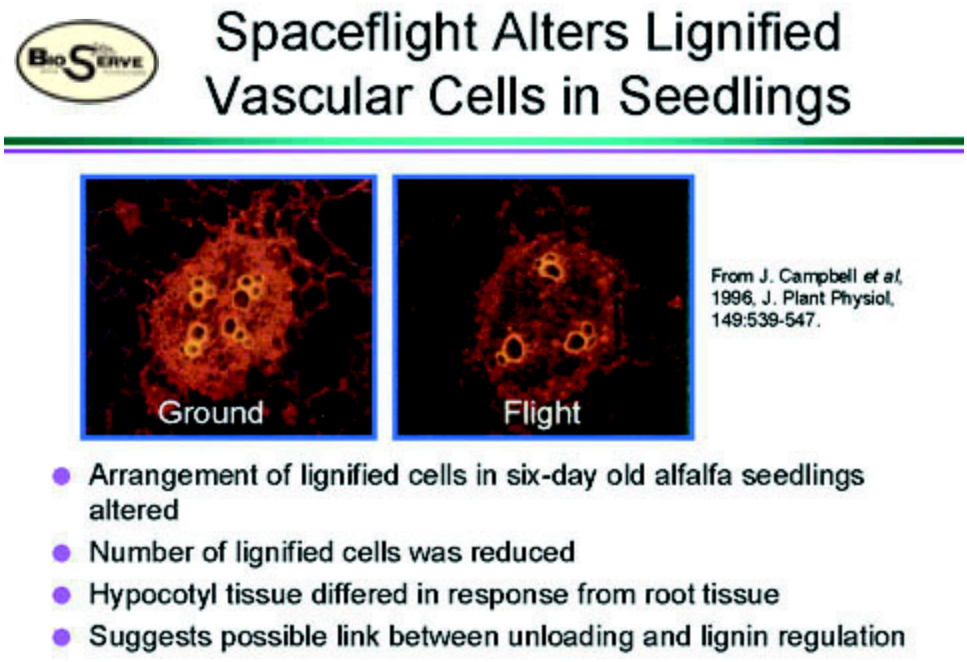


Figure 10. Spaceflight effects on lignin in seedlings.

Thus there was evidence to support the notion that mechanical unloading in weightlessness would in fact affect lignin content. In this case it's looking at the vascular material, but there is certainly reason to believe that it might affect other tissue as well. Other scientific research that has been done in the past has also shown or suggested that lignin content may be reduced in space.

In order to really explore this further, we couldn't limit ourselves to seedling development; we had to study more mature plants. So we developed a piece of hardware to fly on the first Microgravity Sciences Laboratory or MSL-1 (Figure 11). This payload was called the Plant Generic Bioprocessing Apparatus or PGBA. The system has a great deal of capability and in fact is the largest growth chamber that is available, flight qualified and has now been flown. Figure 12 shows an experiment that was done on MSL-1 in

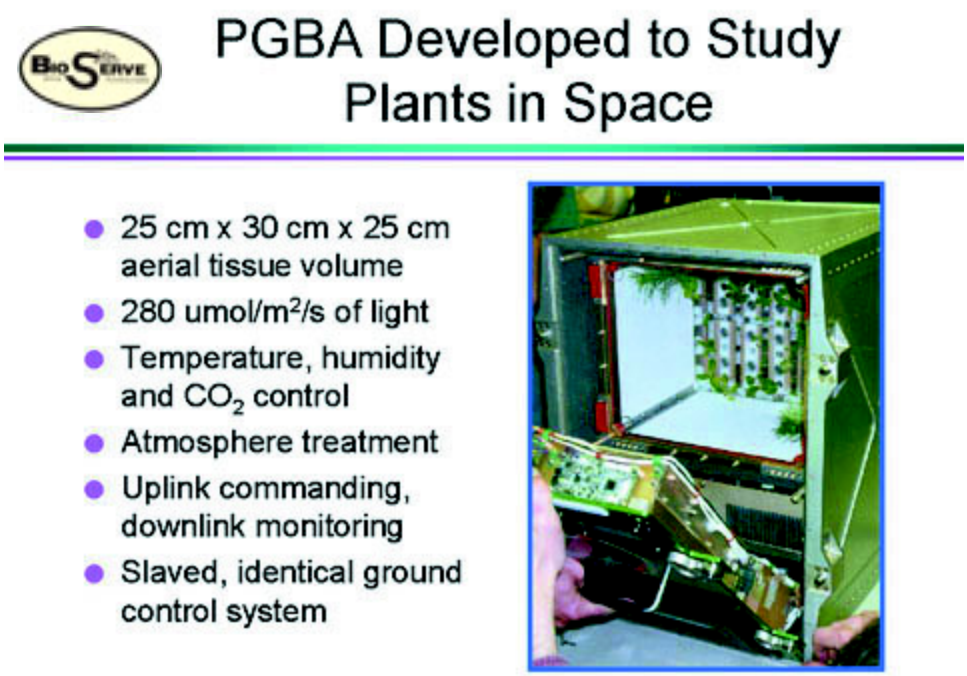


Figure 11. Hardware developed for the study of plants in space.

partnership with Georgia-Pacific, which is the second largest forestry products company in the U.S. (Figure 12). Sales on the order of $13 billion last year puts it certainly on par with NASA's budget. It gives you a scale for a single company, what they might do and how they might benefit from doing research in space.

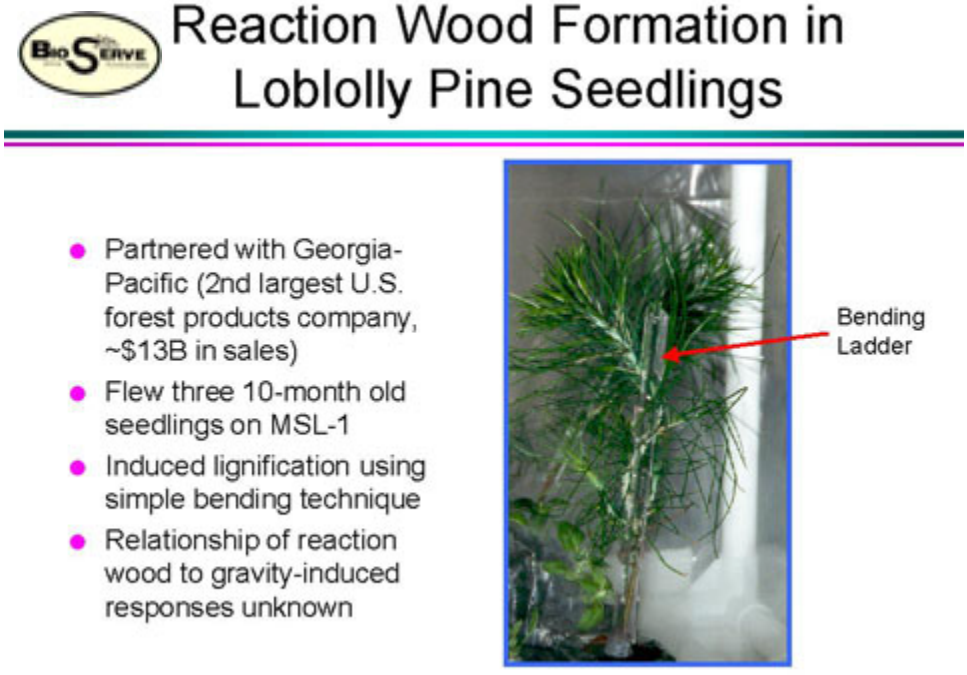


Figure 12. Reaction wood formation in seedlings.

On MSL-1, we flew three loblolly pines seedlings. These are a species of tree in the southeastern United States that is very common and typically used in the paper industry. These are relatively small seedlings. What you see here is a plastic structure, a ladder in which the seedling was bent into a curved shape around the rungs of that ladder. The idea here of course is that in a limited duration in space flight there is not much growth that is going to occur in a tree. On the other hand, we could induce a response called reaction wood formation by creating stresses inside a growing seedling and then look at how the seedling responds in microgravity compared with how equivalent seedlings would respond on the ground. It is not known at this point what the relationship is between reaction wood and gravity, but that question provided the hypothesis for study on MSL-1.

MSL-1 was an interesting mission and there was a lot that was learned from it (Figure 13). One interesting thing that occurred was that MSL-1 was flown twice. The first time it only was up for four days but there were some technical issues during the mission and the Shuttle had to return early. So we ended up re-flying again. The other thing that was unique about our participation in MSL-1 was that the payload was flown in the mid-deck, and transferred back through the tunnel into the Spacelab module for the purpose of demonstrating a rack that would ultimately be flown on the Space Station called the EXPRESS rack. So we essentially became the guinea pigs that allowed the evaluation of the transfer process and the use of the EXPRESS rack for the first time. Figure 13 shows where our payload was located in the EXPRESS rack, which provided us with excellent capabilities.

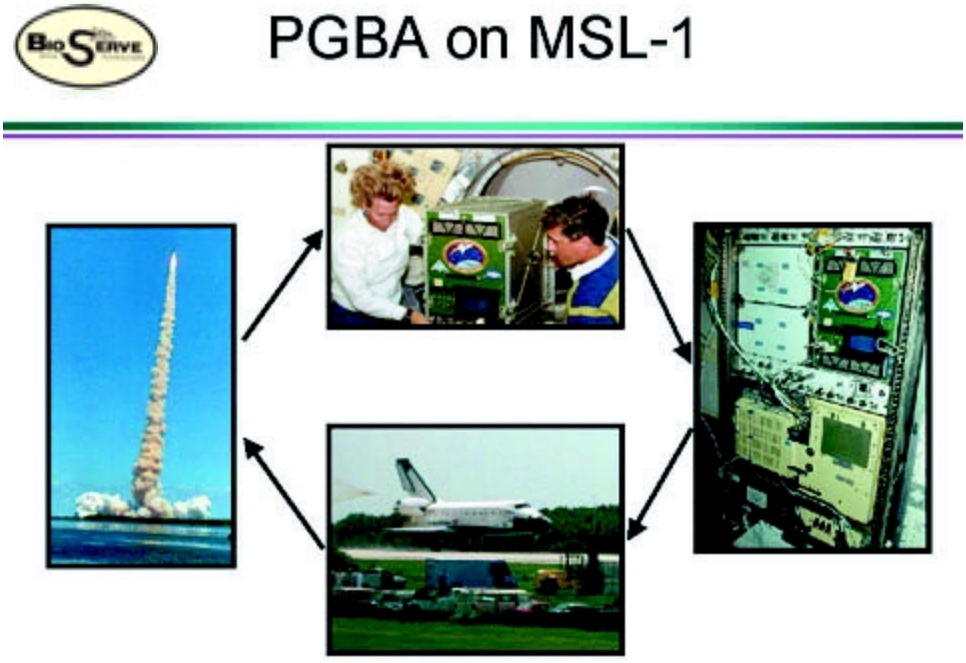


Figure 13. PGBA on MSL-1.

Figure 14 shows initial results that we obtained from the MSL-1 mission (Figure 14). The figure shows one of the seedlings before and after the 16-day mission on STS-94. Of course, as I mentioned, there is not a lot of growth in the seedling itself in terms of increase in height and so forth. On the other hand, there was a great deal of expansion of the needles that you see here, showing basically that the environment in which these seedlings were grown was very healthy with regard to the environmental conditions that were main-

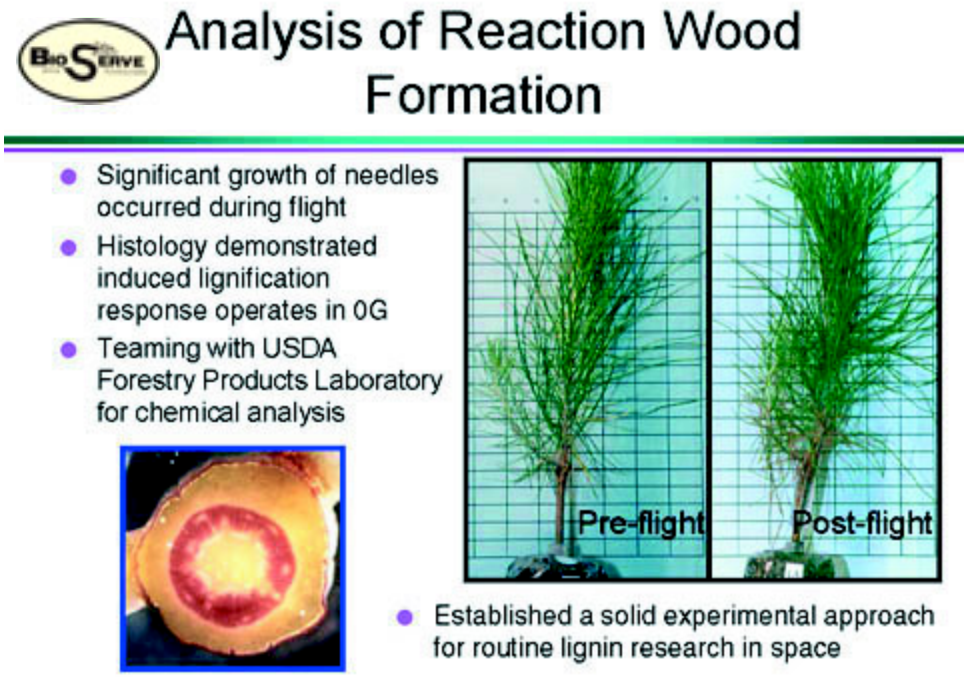


Figure 14. Analysis of reaction wood formation.

tained. This is very important because, as you can imagine, in order to do this kind of research you have to have a very healthy physiological set of conditions for the plants that you are growing, and you have to make sure that the environment is the same during flight as for the ground control. We have, for example, taken extra steps to develop the exact same facility for use on the ground during the mission. Data that would come from the flight itself would be fed into the system on the ground so that conditions were identically matched. There was good growth, good health from these, and we've done some initial histology. What is shown in Figure 14 is the red stained lignin. The lower region reveals a dense region of staining that resulted from the reaction wood process as discussed above.

What we have done is demonstrate a very sound method for doing this research in space. Sixteen days is still very limiting in terms of what you can learn from trees grown over that time period, but it points the way to what we can do on the International Space Station. We are now teaming with the Forest Products Laboratory from the USDA, which is located in Wisconsin, who will be continuing the analysis of the samples from this mission and looking at the overall chemical content of lignin in these seedlings.

It's not only forest products that we are interested in. In addition, we are also interested in the possibility of space flight alterations in plants in the way that they produce secondary compounds (Figure 15). As I mentioned before, phenylalanine goes through these pathways through hydroxycinnamic acid and ultimately forms lignin. If you produce less lignin, then you can imagine that the precursors for that might in fact be channeled in a different direction. What is shown here are a number of secondary compounds that are very close to this pathway. Of course plants are well known to produce thousands of different species of secondary compounds, compounds sometimes that simply are not known in terms of what function they serve with the plant. Many of these secondary compounds are used by the pharmaceutical industry in producing pharmaceuticals. In fact, ten percent of the pharmaceuticals that are used in prescription drugs

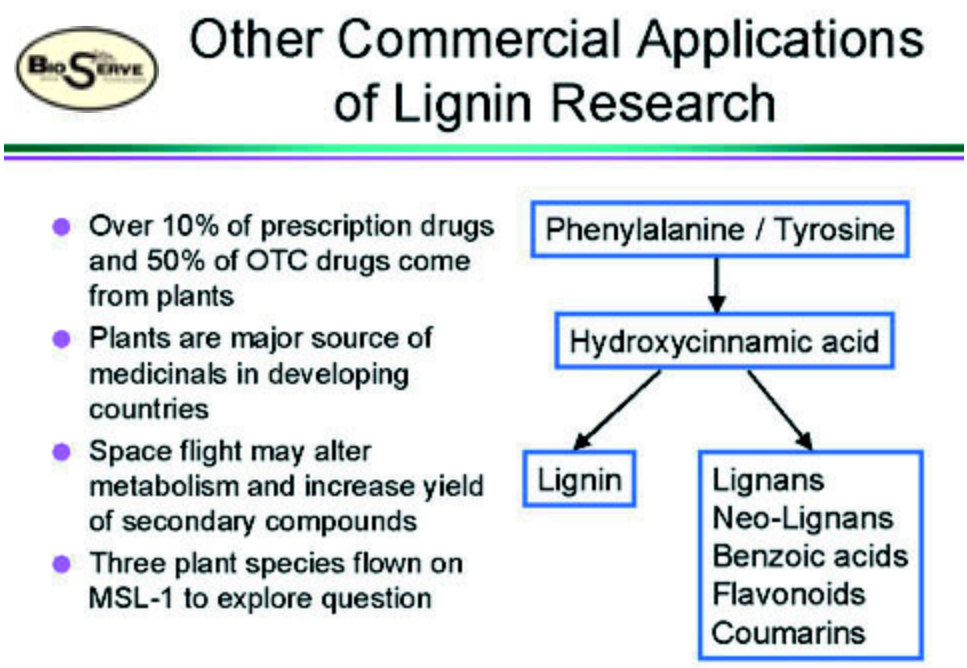


Figure 15. Other commercial application of lignin research.

and 50 percent in over-the-counter drugs are derived directly from plants. In many other pharmaceuticals, drug companies started by deriving the compounds from plants but eventually learned how to synthesize them or produce them in other ways. Plant-produced pharmaceuticals are still a very major component of the pharmaceutical industry, and there is increasing interest through new drug discovery techniques in identifying compounds from plants that may affect or benefit disease treatment.

One of the experiments done on MSL-1 was to evaluate whether pharmaceuticals might be enhanced and whether we can apply information learned to terrestrial drug production. The goal was to further understand lignin regulation, in terms of metabolic processes, and to begin to identify the associated genetic and biochemical mechanisms to create new strains of plants that could be used for producing pharmaceuticals on the ground.

What has been done up to now, as important as it is, is only the beginning. What we are really interested in, is going to Space Station (Figure 16). This is where Space Station will truly shine in being able to support this kind of research, because if you are going to look at lignin regulation in pine species, clearly you need longer growth periods. Three to four months would be quite reasonable.

We are working at this time to form a research consortium that would consist of a number of industry partners. The consortium would provide the funding and expertise for a very focused, say five-year, research period that could then address these kinds of questions. In this way, the role of gravity in lignin regulation and secondary compound production could be ascertained and benefits from using the Space Station by the companies in the consortium could be clearly demonstrated.

Thank you very much.

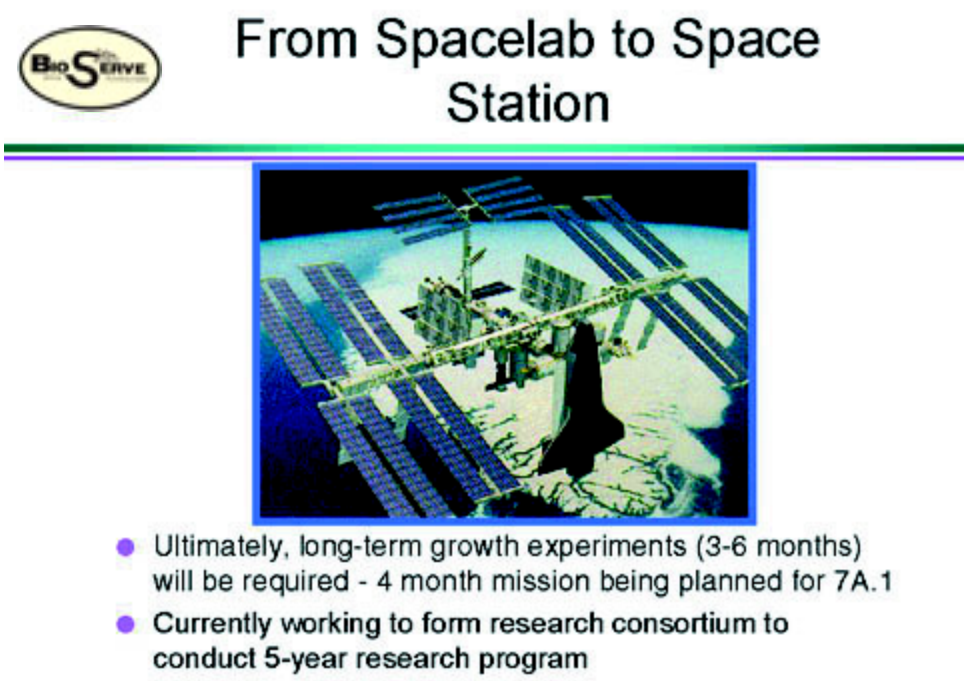


Figure 16. Future research.

As an introduction, this will be similar to what you heard in Dr. Stodieck's presentation. I'm also with BioServe Space Technologies at the University of Colorado in Boulder. In this case, though, I am working with microorganisms. I've heard the word "continuum" used many times in the past couple of days. In some sense I'm going to talk to you about aspects of three different continua. One is our hardware evolution. The second is the continuum of literature, starting from the early research done back in the 1960s that we are still building on today. The third is a parabolic continuum of sorts. There were questions asked earlier about when research is done on the ground, how do we transition that into space, and that is part of this continuum, but from a commercial space center standpoint, our real job is to bring the benefits back down to Earth. Not only are we trying to evolve ground-based research to space, but also bring back what we learn in space for applications on the ground.

The following slides show the hardware evolution. This is the FPA, or the Fluids Processing Apparatus that Dr. Stodieck referred to earlier (Figure 1). It is approximately 4.5 inches long and holds six and a half milliliters total of fluid volume; it's essentially a microgravity test tube. It allows us to keep fluids isolated initially and then mix them once we are in space to initiate a reaction, and then fix or stop the reaction by adding a third fluid. What you see here in the bottom of the slide is the final configuration of having added a fixative on orbit to stop the process.

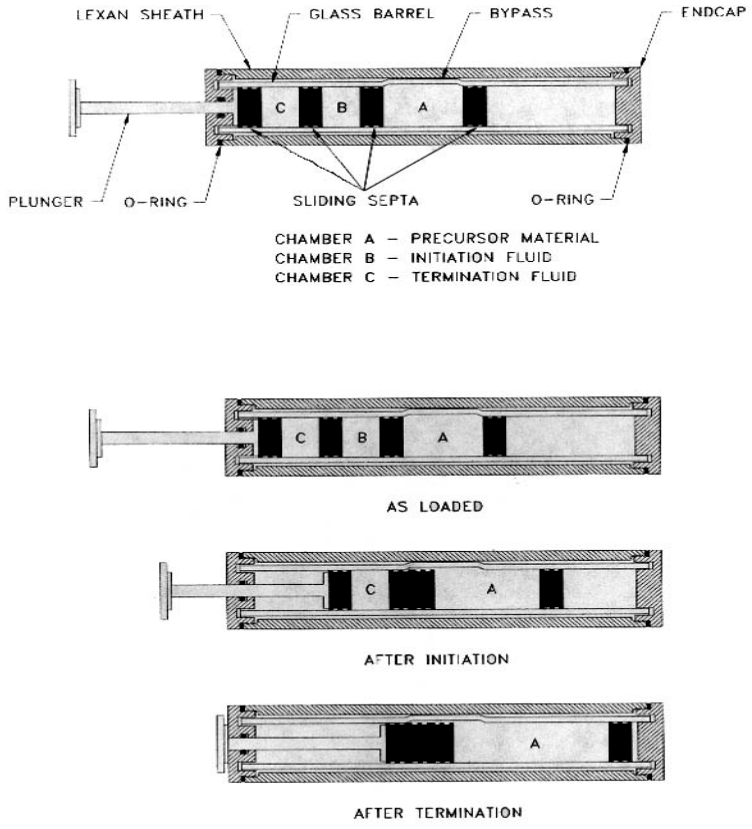


Figure 1. Fluid Processing Apparatus.

This is a photo taken on USML-1, which was the first flight of the Commercial Generic Bioprocessing Apparatus, or CGBA, payload, showing Carl Meade working with the experiments (Figure 2) . You can see



Figure 2. Commercial Gerneric Bioprocessing Apparatus on USML-1. (NASA STS050-301-001)

the FPAs that he had to activate individually, one by one, and the locker that provided a thermally controlled environment, as well as an optical density measuring system so we could monitor sample turbidity and collect real time data on orbit. It turns out that it was very cumbersome to do these things one at a time. So one of our immediate steps after that flight was to design a group activation pack, or GAP, that allows you to turn a crank handle and activate eight FPAs simultaneously, as opposed to doing them individually, and also added a positive third level of containment (Figure 3).

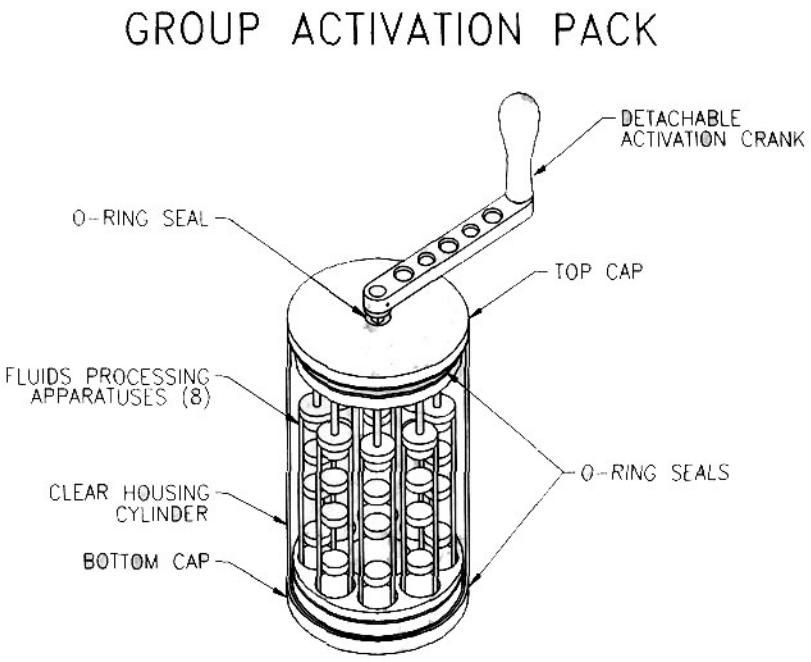


Figure 3. Group Activation Pack of FPA's.

You will see how the CGBA payload continued to grow and evolve. Instead of only having 12 FPAs at a time stored in a separate locker and then processed in the CGBA, we modified the hardware configuration to allow us to have nine of these different gaps processed inside of a single locker. There is a bank of optical sensors in the front that you can't see in this photo, but we could take these out individually and place them in to monitor optical data. This was thermally controlled, to a 37 degrees C set point in this case, to provide a normal physiological temperature environment.

Here is a schematic showing what the CGBA Incubator looks like (Figure 4). It's a middeck locker replacement. It slides out so the crew can access the individual experiments and activate and terminate them in orbit.

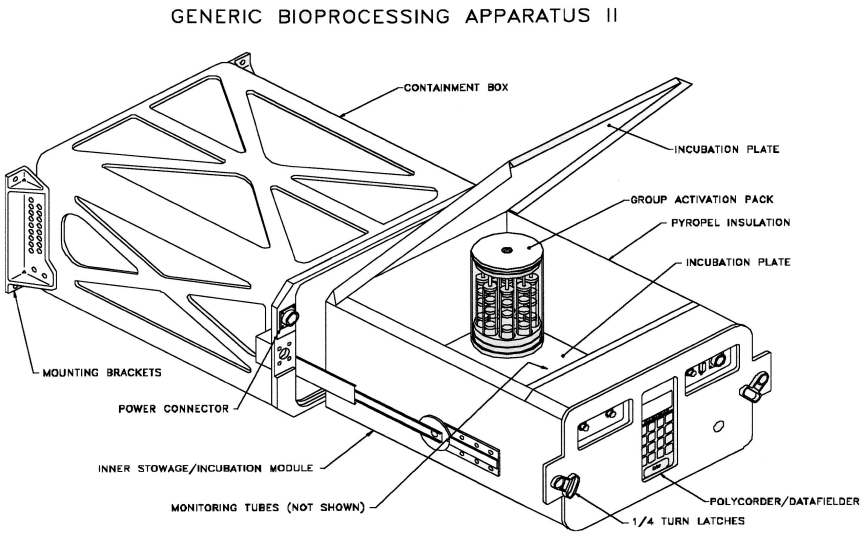


Figure 4. CGBA-Incubator (INC).

Here is a picture of Michael Lopez-Alegria activating one on USML-2 (Figure 5). In some sense, the results from USML-1 marked a milestone in this research, as did USML-2 for different aspects of the

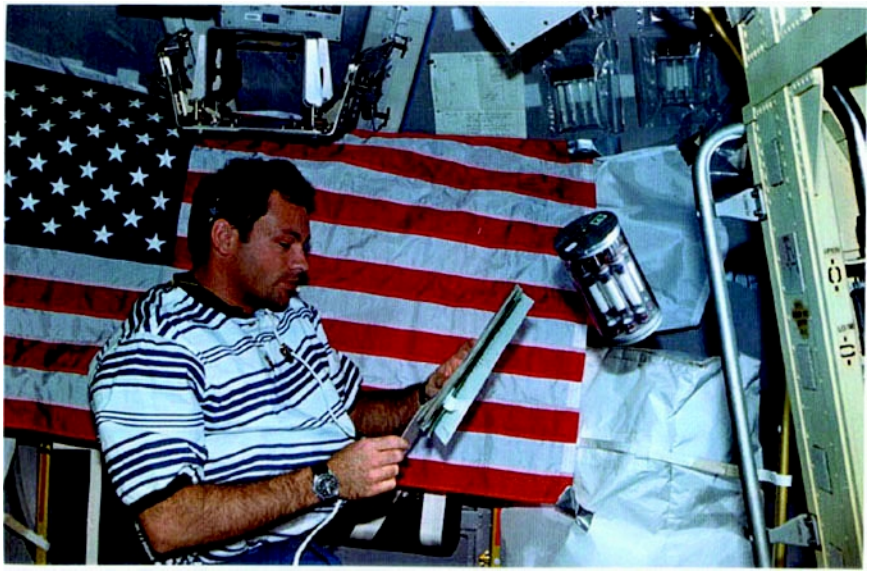


Figure 5. Activation of CGBA incubator on USML-2 (NASA STS073-232-013).

microorganism research that we were conducting. More on that later. We next decided to automate the activation steps. We did this by putting a DC drive motor on the GAP (Figure 6).

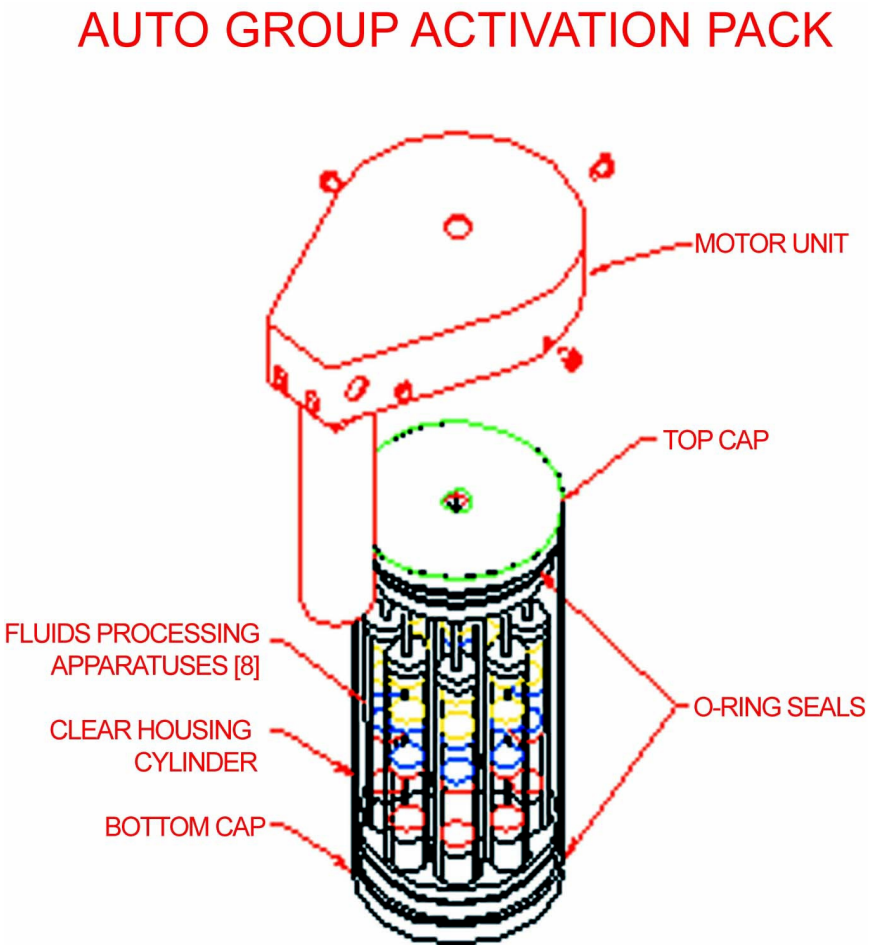


Figure 6. Automated GAP.

The CGBA payload also now incorporates an accelerometer so it can detect launch and begin the activation process after reaching orbit and is now called the CGBA-Isothermal Containment Module, or ICM (Figure 7). A couple of advantages are that crew time is, of course, very hard to come by especially in the first day or so of the mission, and it's often useful if we can get these biological experiments initiated on the first day. The hardware now allows us to do this autonomously, without having the crew involved.

The ICM payload was designed to be transferred onto Mir. Part of the evolution in hardware design was driven by two 4-month stays aboard Mir on NASA-3 and NASA-6. So now instead of being a locker replacement, it's a locker insert and this part is actually slid out of the Shuttle after it is powered down, slid back into Mir and powered up. That's how we accomplish the transition.

This is a photo of the front panel showing what that payload looks like when installed (Figure 8). If you could see this up close enough, you would see it's bilingual, written in Russian and English. This was the ICM payload as modified for Mir.

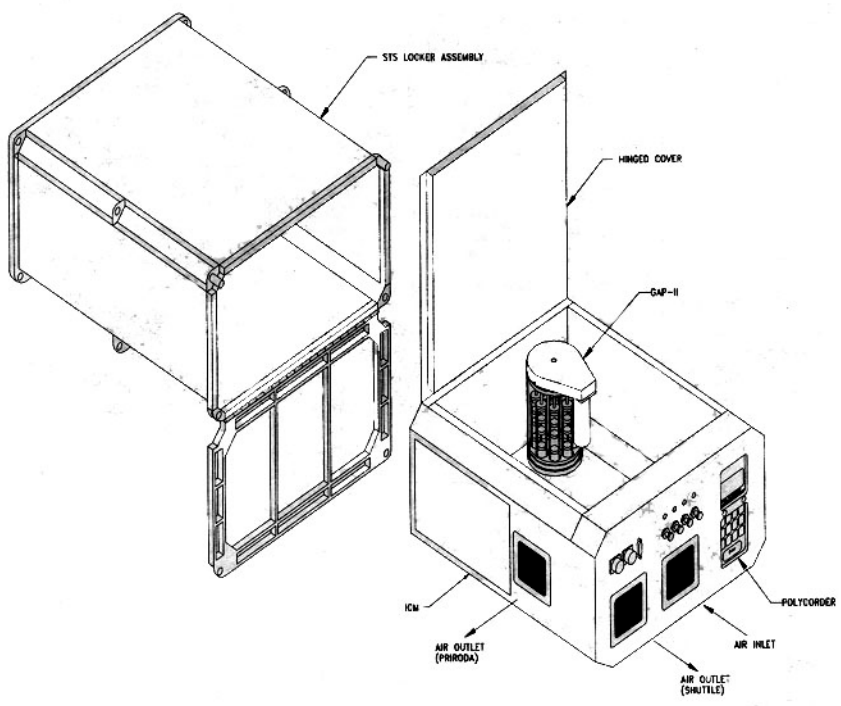


Figure 7. CGBA-Isothermal Containment Module (ICM).



Figure 8. CGBA-Isothermal Containment Module (ICM) Faceplate (as installed).

I can tell you from an operational standpoint that we had one interesting anomaly on Mir. We had a subroutine freeze up during the mission on NASA-6. We didn't know what was causing it then, but every time Dave Wolf would execute a particular command it displayed a garbled screen. We had to do a work-around. Ultimately we were able to correct the problem through a series of iterative messages going up and down to figure out exactly what was going on. When we got the payload back and downloaded the software, we found out that we had had a single bit flip, a zero turned into a one, which doesn't sound like

much, but it can wreak havoc on a computer program. As I said, we were able to circumvent that problem on orbit, but it was interesting to see what had happened. What we suspect was that a particulate radiation hit caused the bit flip, known as a Single Event Upset.

Here is an example of the last step in the CGBA evolution (Figure 9). This is a prototype of the version that flew on STS-95 in October, 1998, and the major thing that has really changed here is there is a much better computer. It's now a Linux operating system. It's a single board computer with a PC-104 expansion bus architecture.

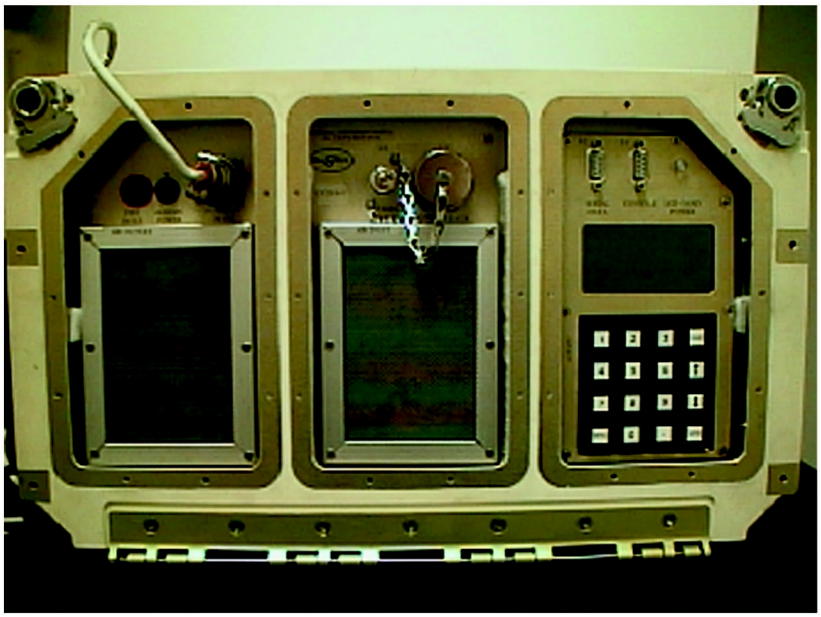


Figure 9. CGBA prototype of module flown on STS-95.

Just to give you a quick research overview without really going into detail, Dr. Louis Stodieck already mentioned earlier that we have supported a number of different kinds of experiments in this payload.

CGBA Science Overview

Previous research has been broadly categorized into the following topics (Table 1). This list gives examples of some of the kinds of things that we have flown, ranging from small whole organisms, invertebrates, brine shrimp, miniature wasps, mammalian cells, viral capsid formation experiments, and protein crystal growth. Some of the early plant seedlings that were germinated inside of a test tube were later evolved into experiments performed inside our plant growth chamber called PGBA. Some other experiments involved pieces of biomaterial and bone, collagen polymerization and fiber polymerization experiments. Finally, we have microorganisms. The microbial research is what I'm going to focus on today to give you an idea of how we have taken some of these basic research steps towards the direction of commercialization and some of the applications that we are pursuing as such.

In all these instances that I identified, all the different kinds of experiments that we've flown, there is a common analytical process that you go through. A lot of these biological and physiological processes have

Table 1. Previous CGBA research subject

Whole Organisms	brine shrimp, miniature wasps, planaria, Killifish, Tribolium, and Drosophila
Mammalian Cells	Lymphocytes, Hematopoietic cells, HL60 cells, GAP junction protein, bone marrow macrophages, spleen cells, CD4 T-cells, A-6 cells, cardiac myocytes, pancreas cells and endothelial cells
Viruses	capsid formation, Polyomavirus, viral infection
Crystal Growth	lysozyme, RNA, oligonucleotides, protein complexes
Plants	seed germination, Arabidopsis, Zea mays, Periwinkle, tissue and suspension cultures, Clover, Alfalfa, legume-rhizobium nodulation
Biomaterials/Bone	fibrin, collagen, pre-metatarsal, skeletal tissue, calcium and cellulose
Microorganisms	E. coli, antibiotic production by Streptomyces and H. fuscoatra, B. subtilus, Rhizobium trifolii, Aquaspirillum magnetotaticum, bacteriorhodopsin, iodide disinfection, biofilms, yeast and S. aureus

shown evidence, both in the early literature as well as some of the work we had done on the early flights, that things happen differently in space. That is step one. It's an observation, if you will.

What we are focused on mainly, especially as engineers, is looking at the underlying gravity-dependent phenomena so that you might be able to start to correlate some of the physical changes with these physiological responses. In other words, start to establish a cause and effect relationship.

Before you can start thinking about commercial applications, you really need to have a little bit more of an understanding, by and large, of what is causing the changes in space. So we spent a lot of time further characterizing work that we had seen in the earlier literature and building on some of the work that we had done both in space and in our labs from ground-based studies. This is a key point right here. The people in industry aren't lined up out there waiting to use Space Station. A lot of outreach and education is required. They are fascinated by it when you can get your foot in the door and begin to explain the possibilities, but space research is still somewhat removed from the mainstream in industry. I know that is changing, and it is nice that we have a Space Station up there now to further this, but it really is a process initially of saying, "Hey, there are a lot of things that happen differently in space; we think that they are related to what you do; here's how we think this might be applicable to your needs in commercial research."

Louis [Stodieck] also pointed out several times that we use a generic approach, a shotgun approach essentially. By looking at many, many different kinds of physiological responses you start to then focus in on the ones that appear more promising, and with that you transition from a shotgun to a rifle. This drives the

need for more specialized hardware that allows you to further investigate specific promising findings, much as the plant growth chamber that he had discussed earlier.

From a science standpoint, the basic understanding we had going into the microbial project in the early 1990s, was that somehow or other microorganisms, bacteria in particular, tend to grow better in a zero G environment. That's not a real clear definition. When I say grow better, there is a 20-minute answer to that, but that is the one sentence answer.

Knowing that a lot of natural products, antibiotics, for example in this case, are derived from these naturally occurring processes, and knowing that the growth process occurs differently in space, led to the hypothesis that if they grow better, maybe they are going to produce secondary metabolites better as well. That was essentially the going-in commercial hypothesis. What we are aimed towards right now is using this knowledge — I will show you this turns out to be true in certain instances — towards improving the efficiency of terrestrial fermentation processes. So we are not talking about making a product in space, at least not initially, but we are talking about understanding a process better as a result of observing it in space, and bringing that knowledge back down to Earth. We are also certainly keeping our eyes open for any kind of novel pharmaceutical products that might occur as a result of being produced in this altered environment.

There is a lot of information on this next chart, but I want to just highlight a couple of things (Table 2). This is the literature continuum I referred to earlier, data from not just work we've done, but work that dates back to the 1960's, initially asking, much as was the case with humans, can single cells live in a zero G environment? In fact, that is what the first experiment proved, that bacteria remain viable; you fly them, bring them back and see that they are still alive.

Literature Review of Earlier Bacterial Space Flight Research

As far back as the 1960s, in the U.S. Biosat-2 program, you start seeing reports of increased final population densities. What was interesting to me here was noting all of the different Spacelab missions appearing in this list. I guess I knew this, but I just didn't think about this earlier when I was putting this presentation together, that much of this research was performed on Spacelab missions. Over and over you see reports of increased cell numbers. Of course some controversy exists, but I think somewhat potentially explainable controversy. Controversy is good. I think this stems, without going into detail, from the different kinds of hardware used, because a lot of these processes are containment geometry-dependent as well as gravity-dependent.

There has been quite a bit of literature and quite a lot published from the early Spacelab missions. Shorter doubling time; earlier entry into stationary phase. Dr. Mennigmann, who I had the opportunity to meet a couple of years ago when I was working in Germany, was the first person I know of that suggested a growth medium dependency, which makes you start thinking that what is going on in the extracellular environment might in fact be affecting the physiology of the cells. We've since established a model based on extracellular effects and now have several publications in Microgravity, Trends in Biotechnology, Advances in Space Research, and Applied Microbiology and Biotechnology, further describing this model. So what we really started working with was trying to understand what was causing these observed changes.

Table 2. Literature review of related science.

Researcher	Flight	Data
Zhukov-Verezhnikov (1962)	Second Soviet Satellite	No changes in bacterial cell viability
Mattoni (1968)	US BIOSATELLITE II	Increased population densities
Tixidor (1985)	Salyut 7, Cytos 2 Experiment	4-fold increase in MIC of colistin and kanamycin. Stimulating effect on cell multiplication.
Moatti et al. (1986), Lapchine et al. (1987), Lapchine et al. (1988)	Spacelab D-1, Antibio Experiment	2x increase in MIC for colistin. No difference between μ-g and on-board 1-g centrifuge samples. Stimulating effect on cell growth
Mennigmann and Lange (1986, 1988)	Spacelab D-1, Biorack Experiment	B. subtillus increase in growth rate and in total biomass in space. Lag phase ended approx 5 hours earlier in space
Ciferri et al. (1986, 1988)	Spacelab D-1, Biorack Experiment, Genetic Recombination	Enhanced conjugation in space. Increase in cell number observed
Bouloc and D'Ari (1991)	Biocosmos 2044	No differences between flight and ground cultures in the growth yield per gram of carbon, mean cell mass, or level of expression of the SOS response
Tixador et al. (1992)	IML-1, Antibio Experiment	First observations show cell growth rate more important in the flight cultures. Results can explain previous observations showing an increase of antibiotic "resistance" for inflight cultures
Bouloc and D'Ari (1992)	IML-2	Study effects of microgravity on the cell's microenvironment and bacterial membrane transducing pathways
Mennigmann and Heise (1994)	IML-1 and Spacelab D-2	Suggested medium dependency of gravity effect on growth

This was a very terse summary to wrap up a number of experiments (Table 3). It is interesting that two of the main points on this chart actually came from USML-1 (STS-50) and USML-2 (STS-73) data. A typical bacterial growth curve consists of three phases. Initially, the number of cells remains constant through the first phase, called “lag”. They then begin a logarithmic doubling phase until they finally reach a saturated concentration, called the “stationary phase”.

Table 3. CGBA bacteria flight experiments.

Initial ground based studies	Space protocol, cell and medium selection
STS-37 and 43	Hypothesis development, feasibility/ viability studies
STS-50	Nutrient adaptation, liquid/gas interface, geometry effects
STS-54	Temperature effects, daily optical density measurements (37°C)
STS-57	Antibiotic effectiveness
STS-60	Antibiotics, high resolution Optical Density (OD) growth curve
STS-62	OD to study lag phase, flocculation behavior (37°C)
STS-73	Additional lag phase resolution from continuous OD data (37°C)
STS-77, 80 and 95	Antibiotic production pilot studies

CGBA Bacteria Space Flight Experiment Evolution

In a nutshell, when I say bacteria grow better in space, what we are seeing is an earlier entry into the doubling phase, or a shorter lag period, and a much higher final cell concentration when they reach the stationary phase. For STS-50, we were really focused on final cell numbers; on STS-73 we were focused on lag phase transition to logarithmic growth. Due to the transitory nature, it's difficult to collect data on the lag phase duration, but as I mentioned earlier, we had continuous optical density sensors now so that we could monitor the growth curve in real time on orbit and look for that transition point (from lag to logarithmic phase).

The research continuum goes on, I guess, with STS-77 being the first experiment marking a transition of sorts. STS-73 was the last one we did on this basic growth theme, all the time with the idea that we were going to eventually apply it in this direction. On STS-77 we flew an experiment with Bristol-Myers Squibb exploring the secondary metabolite production, in this case of an antibiotic called Monorden. This follows suit with Dr. Mennigmann's suggestion that a lot of these responses appear to be medium-dependent, as well as containment geometry-dependent, species-dependent, on and on and on; there isn't going to be a single answer as to what gravity does or doesn't do to these microorganisms; there are about a half a dozen caveats that have to go with each explanation.

This was one of the more interesting findings here: we observed a statistically significant higher yield of almost 200 percent of Monorden on STS-77; so almost three times as much of the antibiotic was produced in space as occurred in a matched ground control. The difference was most noticeable from a visual

standpoint, in the amount of pigment produced during this process. It is not exactly the antibiotic, but it's associated with it. (Reference: *Trends in Biotechnology* 16(9): 369-373, 1998)

Again, this was performed in a test tube like device. A test tube is not the best environment to do this in. So, even though we had 200 percent more [antibiotic] in space, we are still an order of magnitude or more, less than what can be achieved under optimal fermentation conditions in one G. With the idea of trying to match these experiments for comparison of flight to ground, you have to compare apples to apples, at least initially. Even though we know this isn't optimal, the idea comes from the test tube and then gets scaled up into specialized hardware.

This photo showing the new design is from a newspaper article that came out from Hartford, Connecticut, *The Hartford Courant* (Figure 10). It is a device that we designed as a follow up that flew on STS-95 and is called the gas exchange fermentation apparatus, or GEFA (Figure 11).

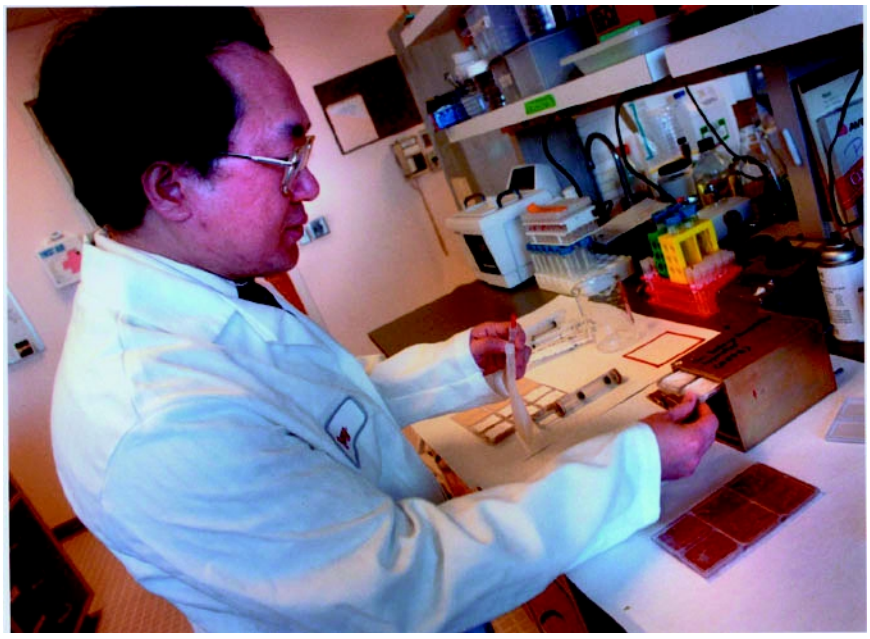


Figure 10. Raymond Lam (Bristol-Myers-Squibb) fits samples into the hardware for STS-95. (John Long, *The Hartford Courant*)

This was a first step towards optimizing the space flight hardware. These trays contain cells that are contained in gas permeable bags and then sealed up in this box with gas permeable end caps. This is a step in the process of evolving the hardware based on positive findings. We found that we needed better aerobic conditions. This allows us to provide more oxygen and increased surface area for the cells to grow.

The question then becomes, why? Or, what caused what we have seen and observed and read about. The answer why, I think, with bacteria is simplified. They make a nice simple organism to study because theoretically you can almost rule out any internal effects of gravity and focus on the extracellular environment. (Reference: *Trends in Biotechnology* 16(9): 369-373, 1998)

What I am trying to illustrate here are the altered fluid dynamics and reduced mass transfer that occurs in the extracellular environment. It has been hypothesized that in a microgravity environment you get a

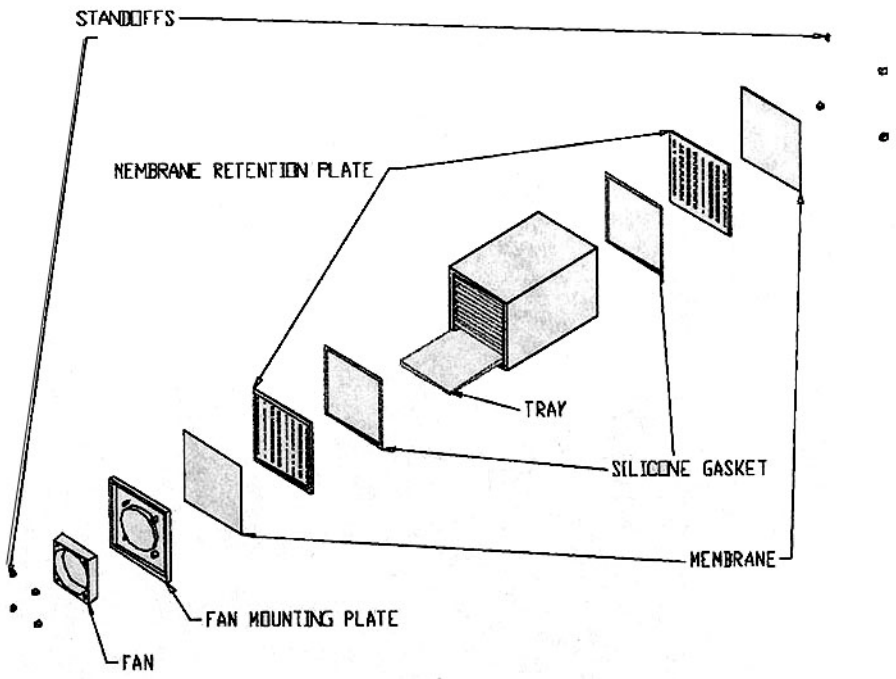


Figure 11. Gas Exchange Fermentation Apparatus (GEFA).

build-up around the cell of the excreted metabolites, whereas in one G you are always falling away from that. That has been referred to as the "dirty bathwater" phenomenon. That sounds negative, but then when you talk about the other extreme, more even cell distribution over time, that sounds positive. So there is very much a differential effect going on.

Since I'm an engineer, I like to look at things like black boxes and treat these cells as such with mass throughput, then start analyzing the forces. Here is the force due to gravity causing sedimentation of the cell. You take that away and other forcing functions become dominant. What we think is happening is that a change in the physical environment is indirectly affecting the chemical environment surrounding the cell. The altered chemistry then gives rise to an altered physiological response. This is the model of cascading events we are working on.

Bacteria, as I said, make an interesting example. There are some illustrated curves here (Figure 12). Particles (suspended in water) that are less than one micron in size are much more influenced by Brownian motion than they are by sedimentation. It is a square root of time function, as described by Einstein, and is random diffusion for very small particles in the absence of a forcing gradient. For larger particles the dominant force of gravity is very obvious, and diffusion becomes negligible essentially after the particle gets large enough.

Bacteria fall in this gray zone here (in the overlap between diffusion and sedimentation). That's what makes them interesting. Initially diffusion is a more dominant function, but cumulatively speaking, sedimentation becomes more influential here (after the break point) — this just has to do with the distance that the cell has moved from its origin from the two forces trying to move it, gravity and diffusion. Of course the actual net motion is a vectorial combination of the two. This is what causes analytical problems by giving us a lot of nonlinear relationships. But this also makes it more interesting to study.

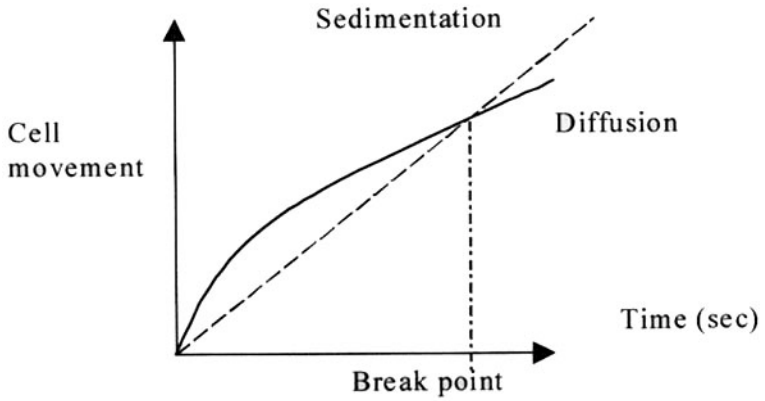
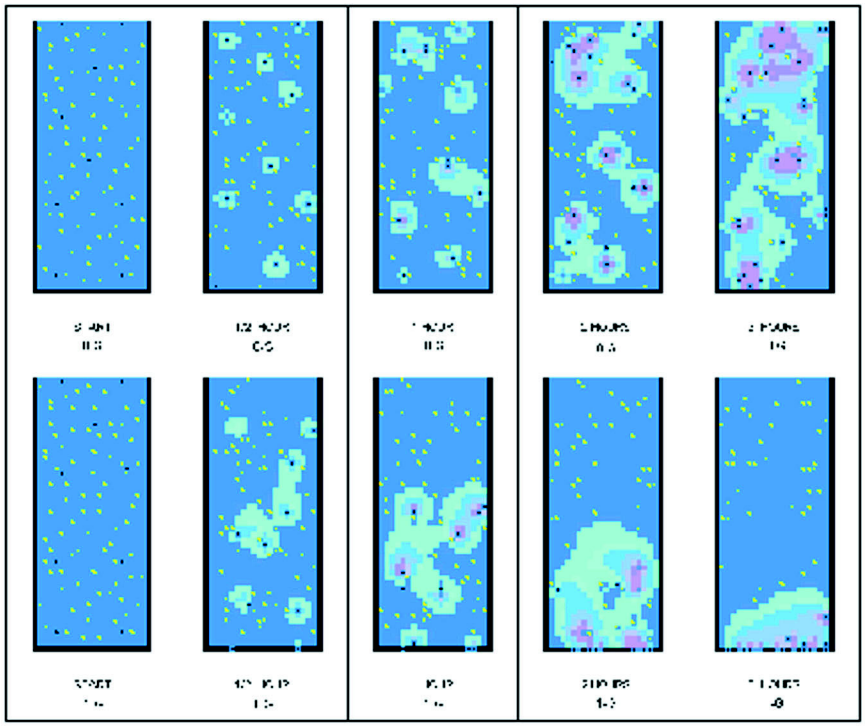


Figure 12. Adapted from Snodgrass, 1999.

To give you an example of this nonlinearity and to show you why you can't simply take centrifuge data, one G data, and extrapolate backwards, this chart represents on the y axis a percentage of waste that remains in the vicinity of the cell. If you look at zero G, this dark curve going through here, versus one G, you see this transition point right here where the one G is initially falling away and then it gets caught up, whereas in zero G you've got a different forcing function when you take away sedimentation. (data not yet published)

I don't want to go into a lot of detail on these. I want to show you a couple more examples of some nonlinear relationships associated with the cells. This is all defined by altered basic physical processes which are suggested to affect the physiology.

We turned the static model into something a little more visually appealing. This is a finite element Agentsheets model (Figure 13). The cells that you see, the black dots, settle to the bottom in one G over time. The


Figure 13. From Lanning, 1998. Top row of models represents results in microgravity, bottom row of models represents results in one gravity.

difference in the concentration of byproducts (red) shown forming around the cells is how we are trying to quantify this build-up of waste around the cell in zero G vs. one G.

A substantial part of the work that we are doing involves ground-based research using a device called a clinostat. The clinostat simply rotates one of the test tubes about its long axis and creates a state of "motion-lessness" for the suspended particles, if you do it right. Not weightlessness, but you take away the external motion.

I spent a year in Germany learning about clinorotation in Dr. Briegleb's lab at the DLR in Cologne. The clinostat gives us a tool that allows us to manipulate the effects of gravity on Earth. We are getting to the point where we can really predict what will happen in simulated zero G versus a one-G baseline. You see basically the same phenomena occurring in space, a shorter lag phase and higher final numbers. Under hypergravity, we can shorten this lag phase up even more but end up with fewer numbers of cells. It's a differential response as a function of gravity. [Data not yet published]

Just to give you an idea of the shape of the curve, the important piece here comes from hypergravity acceleration. The increase in final cell density, one G being the baseline, shows up to 100 percent more in space, in zero G. There is a flat portion out to about 10 G, and then it begins to drop off. It has to do with the fact that the cells and the byproducts that they are excreting are affected differently because of their different sizes and densities under the same forces of gravity. [Data not yet published]

Here is an example of where we are taking this applied research. This has been the most exciting finding so far in terms of starting to think about how we can apply this information for terrestrial processes. We've now been able to normalize the increase in cell mass with respect to the amount of nutrient consumed for cells grown on a clinostat and, more recently, in space (on STS-95) but we don't yet have this analysis completed. It turns out what we are seeing, over time — it gets statistically significant at about 108 hours into the growth phase — is that not only have more cells been produced on the clinostat, they are doing so with less glucose consumed. So they are growing better, but needing less amounts of nutrient.

The bottom line of what we are looking at is, by increasing the understanding of how gravity influences these processes, the first step is taken - and specifically here in secondary metabolite production - towards a commercial application of the space research. We are now trying to mimic this response (in one G) of higher specific productivity based on what we think is a higher growth yield from the same amount of nutrients.

It turns out in the pharmaceutical industry these days, there are three areas you can try to optimize. One is you can try to improve the organism; the other is the nutrient; and the third is the process efficiency. I'm told by and large, that the industry feels the first two are pretty much peaked out. So if we can increase even a percentage point or two in process efficiency, that starts to translate into millions of dollars saved per year. That's where the interest is lying, to try to improve upon the efficiency of terrestrial fermentation based on knowledge gained in space. We are also looking for altered byproduct structures, of course, but this you get for free because whenever you are analyzing yield efficiency, you are also analyzing the compound makeup with high performance liquid chromatography (HPLC). Maybe there is going to be a beneficial change in what the cells produce, not just how they produce it. We haven't seen that yet, but we've only flown two organisms.

In summary, from an economic standpoint, and Bristol-Myers Squibb is the company that we've been working with on these antibiotic experiment productions, if you look at their 1996 profits in terms of their annual report, it's $2.9 billion from pharmaceuticals, and the majority of this came from antibiotics. So every little bit of increased efficiency here leads to a tremendous savings in their production costs by scale of economy. That is really where we are focused, taking this knowledge gained from space research and looking for ways to use it to improve terrestrial fermentation efficiency. I certainly don't think we are going to see a 200 percent increase. But if we produced even a one percent increase, that would be substantial, and that's really what we are aiming this towards. That's where it becomes more of an applied process now. Someone mentioned the other day waiting seven years for a flight, I believe. This launch was USML-2 (Figure 14). We had to wait through six launch attempts for this flight. It got off on the seventh. I can understand what it means to deal with delays, especially from a biological sample standpoint, but it was a beautiful launch when it finally got off.

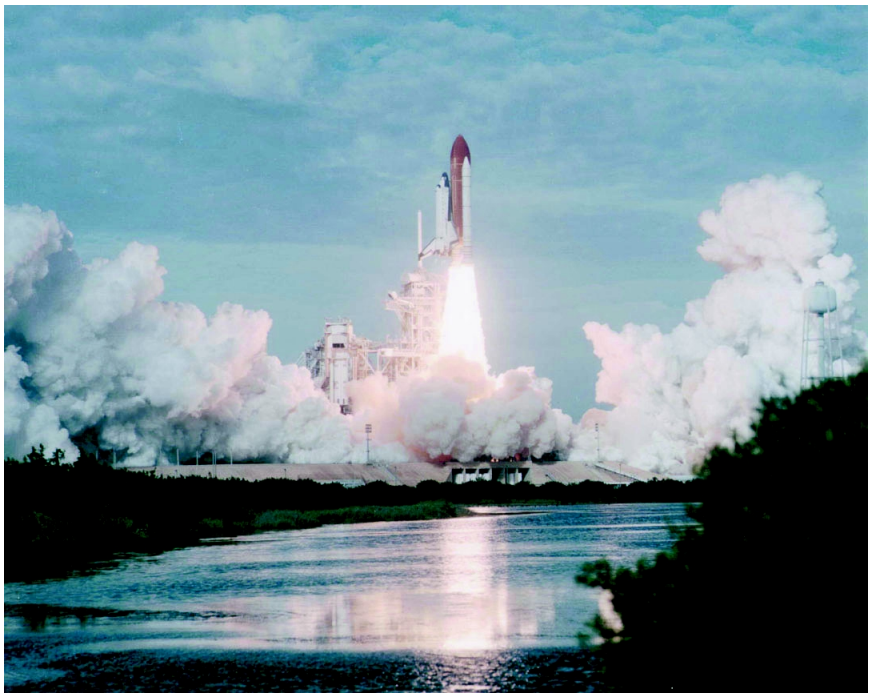


Figure 14. Launch of STS-73/USML-2.

Thank you very much.

<u>Reference List:</u>

Klaus, D.M. (1998) "Microgravity and its Implication for Fermentation Technology". Trends in Biotechnology 16 (9), p. 369-373.

Lanning, C. (1998) Undergraduate Research Opportunity Program (UROP) and Independent Study, University of Colorado, Boulder.

Snodgrass, A. (1999) Undergraduate Research Opportunity Program (UROP) and Independent Study, University of Colorado, Boulder.

Question and Answer

DR. ROSS: I would like to ask Dr. Klaus whether or not you had to space harden your chips? That is not a trivial thing to have a zero flip to a one.

DR. KLAUS: On that particular payload, no, they were not space hardened. It was an off-the-shelf data acquisition system. One of the other ways around that is to run a dual processor where you are doing a continual check back and forth, and we are looking into options like that for Space Station use.

What I would like to do is to briefly review the flights that we had with the Spacelab missions and I will show you some results we obtained. I would then like to jump to the next step, presenting the contributions of the Spacelab missions to our next phase of activities which is the International Space Station, particularly the commercialization area. I'm going to spend the majority of time on the commercialization part.

This is a chart showing the five experiments that we conducted from 1992 to 1995 (Figure 1). The beginning and the ending ones were with Spacelab, and the other three were with Spacehab. Since 1995 we have been involved in space station activities including the Mir Station. In addition, we also participated in the historic Shuttle mission, STS-95.

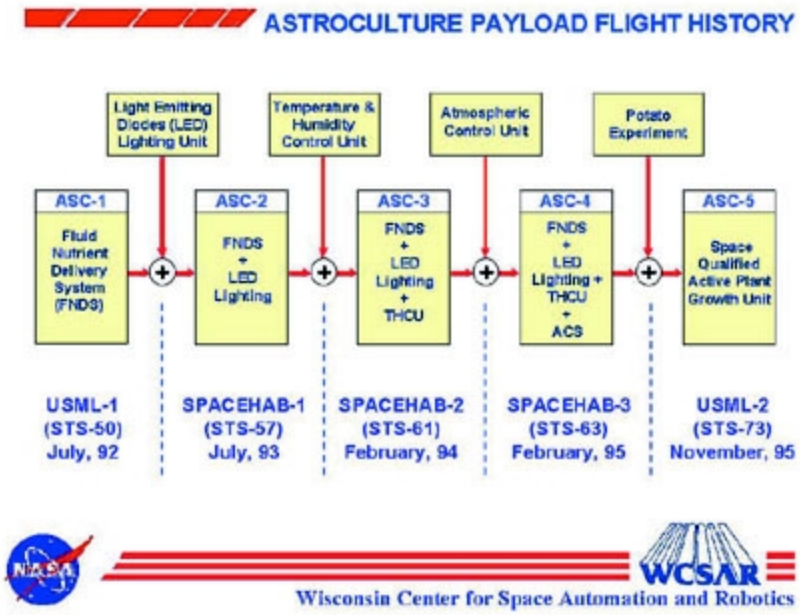


Figure 1. Wisconsin Center for Space Automation and Robotics (WCSAR) flight experiments.

The first Shuttle experiment was particularly critical to us, because it solved a fundamental problem for growing a plant in space with the delivery of nutrient solution to the plant rooting zone. There are many methods available to deliver water and nutrients to plants. The particular approach that we developed is called an active Fluid and Nutrient Delivery System (FNDS). What I mean by active is that it actually causes a net volume or mass transfer into and out from the plant rooting area. We successfully demonstrated the functionality of our FNDS in 1992 with USML-1. Then we integrated a lighting unit into the system. This lighting unit is also very unique. Instead of using a fluorescent light, we were using light emitting diodes (LED). The particular LEDs that were used are a low energy and low heat lighting source, which produce a very narrow spectrum of wavelength that plants need. The integrated system was flown on Spacehab-1 in 1993. Once the lighting problem was solved — by the way, WCSAR has a co-patent on the lighting unit system — we moved on to the next research subject, the development of a temperature and humidity control system.

In late 1993, WCSAR invented a unique humidity control system called the ASTROPORE™ (a trade name and also patented technology). ASTROPORE™ integrates humidification, dehumidification, and condensation recovery features into one unit. This technology was successfully validated in February 1994 on the STS-61 (Spacehab-2) mission. The next environmental control technology that we developed was an atmospheric control including CO_2 control and ethylene removal. As we know, in an enclosed environment plants will release ethylene. Excessive ethylene levels will cause plants to be premature and will ultimately result in unsatisfactory scientific results. WCSAR's ethylene scrubber could effectively control the ethylene level in the enclosed environment under 50 parts per billion. As a result of this development, we also acquired a patent. This atmospheric control unit was then integrated into the plant growth unit and validated on the STS-63 mission. On this mission, we flew two types of plants: super dwarf wheat and Wisconsin fast plants that could generate seeds within 10 days. At this point we really developed a space qualified active plant growth chamber. WCSAR's plant growth unit or ASTROCULTURE™ unit (Figure 2) provides a chamber totally enclosed from the cabin atmosphere, an active fluid nutrient delivery system,



Figure 2. The ASTROCULTURE plant growth unit.

an active temperature and humidity control unit, a LED lighting system, and a CO_2 and ethylene control unit. This was the first chamber available for NASA to conduct plant research in the microgravity environment. On STS-73 (USML-2), we flew the potato cuttings. The objective was to determine whether the plant growth chamber could provide sufficient conditions to form the tubers. As you know, the potato requires demanding environmental conditions, such as precisely controlled temperature, humidity, and CO_2 concentration. This picture shows the results we obtained. Five potato cuttings were flown and five tubers were formed (Figure 3).

Successful STS-63 and STS-73 missions have concluded that WCSAR is able to provide the environmentally controlled chamber for plant research communities to conduct research in space. The ASTROCULTURE™ plant growth unit is a single middeck locker equivalent payload. It provides a small chamber which is suitable for conducting some fundamental plant physiology studies but it is not suitable



Figure 3. Potato cuttings grown on USML-2.

for conducting commercially oriented plant research simply because it's too small. Based on that, WCSAR has developed two larger plant growth units: the Advanced ASTROCULTURE™ (ADVASC) unit and the commercial plant biotechnology facility (CPBF).

The ADVASC payload consists of two middeck-locker-equivalent inserts. One insert contains the control and support systems such as a computer and data acquisition unit, and power conversion and conditioning units. The other insert contains the plant growth chamber and it's supporting subsystems. The plant chamber insert provides a chamber with a net plant growing area of approximately 540 cm^2 and a net growing height of 34 cm. The two inserts are connected together by electric cables and pneumatic hoses after being installed into the EXPRESS Rack. The two inserts can be transported to and from ISS as separate units. Likewise, the ADVASC-SS insert can remain on ISS and only the ADVASC-GC insert needs to be transported to and from the Internation Space Station (ISS) to accommodate different plant experiments. The CPBF will occupy one-half of an EXPRESS Rack. It provides a net plant growing area of approximate 2580 cm^2 and net growing height of at least 42 cm. In addition to all the features that ADVASC has, the CPBF provides a double-contained soft-glove extension to allow the crew to sample the plant materials, re-establish the experiments, and re-configure the experiments. The size of the CPBF plant growth chamber is sufficient to conduct a number of commercial and Advanced Life Support plant experiments that involve determination of crop growth rates. Both ADVASC and CPBF integrate proven ASTROCULTURE™ technologies, an advanced auto-prime system, fault tolerance and recovery technology, and state-of-the-art control software to increase overall system efficiency, reliability, robustness, and flexibility.

This picture shows that the CPBF is installed in the EXPRESS rack (Figure 4) which is located at Marshall Space Flight Center. This is a prototype of CPBF, which has identical functionality, and chamber volume to the flight unit, but it's not space qualified, i.e., the materials and the fabrication procedures do not meet space qualifications. However, it does represent a high fidelity in performance. This is part of our commer-



Figure 4. CPBF installed in the EXPRESS flight rack.

cial applications. For example, American Ag-tec International, a Wisconsin based seed development company, approached us and asked us to develop the technologies which will produce the elite and pathogen free potato seed stocks, called Quantum™ Tuber, at a volume of two million tubers per half year. The difficulties for developing such technologies are (a) the need to assure a seed production cycle at an average of 45 days, (b) to develop a massive network communication scheme that controls and monitors 700 to 1000 small chambers, and (c) to develop fault tolerance and recovery algorithm for each chamber and the network. After about two years of investigation, this technology has been developed by WCSAR and is ready to be put on the market. We were also approached by another major seed company which is a leader in soybean development. The company spent several million dollars each year trying to create a first-to-market hybrid seed. The biggest challenge to the company is how to effectively reduce each seed-to-seed growth cycle and so to reduce the entire period for the massive multi-generation back crossing. Currently, each seed-to-seed growth cycle typically takes 100 to 120 days. WCSAR has successfully demonstrated to Pioneer Hi-Bred International that by using CPBF technology, originally developed for space-based plant research, the ability to significantly reduce the seed-to-seed cycle to an average of 62 days.

Let me take a few minutes to describe one of the experiments that WCSAR conducted on the STS-95 mission. This particular experiment was to transfer the desired gene traits into plant target material and to investigate whether the microgravity environment could stimulate the transformation of the genes. The particular seed that we used was soybean. Substantial ground study has shown that the efficacy of the transformation is in the neighborhood of 0.2 to 0.5 percent. In the STS-95 experiment, we flew one thousand seeds. The post-mission analysis conservatively showed that increase was more than 10 fold compared to a control experiment conducted on Earth.

This single success was warmly and cautiously received by industry. They liked the results and wanted to engage in these activities, but were reluctant to make significant financial commitment. To increase their confidence level, we have requested several flights from NASA HQ such as STS-101, STS-107, and so

forth. We are going to do more gene transfer experiments to validate the results. This is a picture showing our future major research activities. What we are going to do is conduct the gene transfer process in the microgravity environment to introduce the foreign DNA structures and genes into the crop materials, often referred to as the target material. After the target material receives the gene traits, they will be regenerated, again in microgravity and using the CPBF, to produce the breedable transformed seed (BTS). BTS will be brought down to the ground for elite parent seed (EPS) production, using an accelerated plant growth facility developed by WCSAR. EPS will then be used for the massive production of commercial seed. This is what we are doing and this is what we will be doing in the next five years.

The last picture I am going to show you indicates the space-based research activities that WCSAR will be involved in (Figure 5). These two lines show the traffic activities for the Advanced ASTROCULTURE™ payload. The last line shows the traffic activities of the commercial plant biotechnology facility (CPBF). It can be seen that we have lots of flights, lots of experiments to do, and will be very busy. Hopefully, we will generate great results.

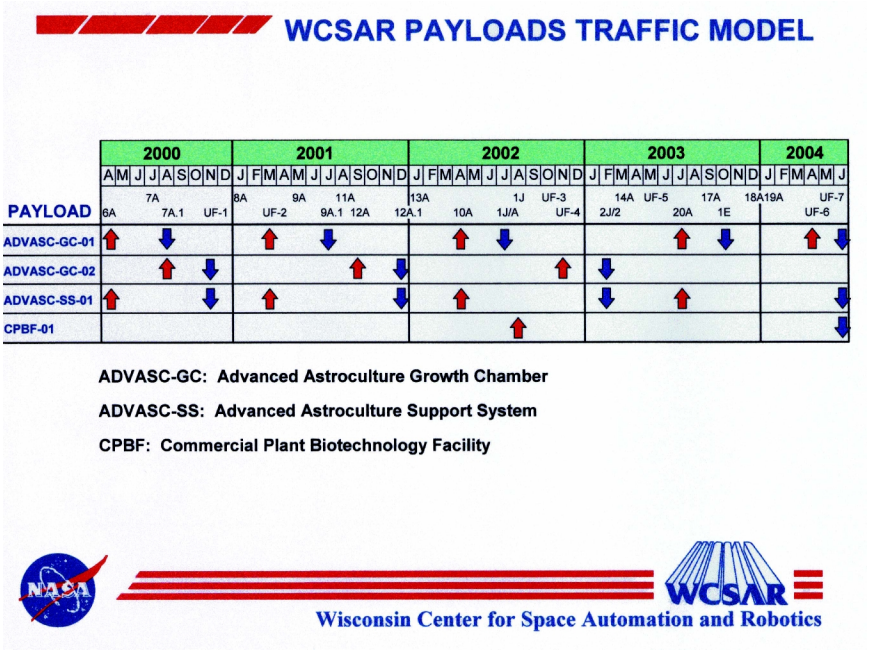


Figure 5. Future space-based research activities for WCSAR.

Thank you very much.

I'm here to talk to you about the Center for Advanced Microgravity Materials Processing (CAMMP), a partnership between government, academics and industry which is in Massachusetts (Figure 1). This is Cape Cod and the islands.



Figure 1. Cape Cod, Massachusetts, home of CAMMP.

Industry, the chemical process industry, is really not interested in space at all, to be quite frank, unless it can be used to bring their products to market quicker. In industry, it's not the initial investment; it's the time to market, to capture market share. That is what we are trying to do.

This is the philosophy behind bringing a university and government together (Figure 2). The university creates knowledge. We intersect with our industrial colleagues to create jobs and wealth and develop products. And NASA, as I see it, and the government in general, provide the infrastructure opportunities and seeds to nurture those things. CAMMP lies directly in the middle.

The objectives we have at CAMMP are really multifold (Figure 3). The first one is to develop a knowledge base in order to allow U.S. industries to make intelligent decisions, target high commodity and specialty products for improving processing primarily on the ground; but also to do some things in orbit in terms of product development, and develop an infrastructure friendly to commercial development. What I found that means is, I have a lot of companies that are interested and they are willing to pay, if I can fly their experiment within six months of the time they show up. Right now that is a difficult thing to do in the space business, but I think that's a target that we all have to go after if commercial space is going to be involved, at least with the chemical process industry. We do have a component to stimulate science and technology in K-12 education, and we also are here to promote international cooperation.

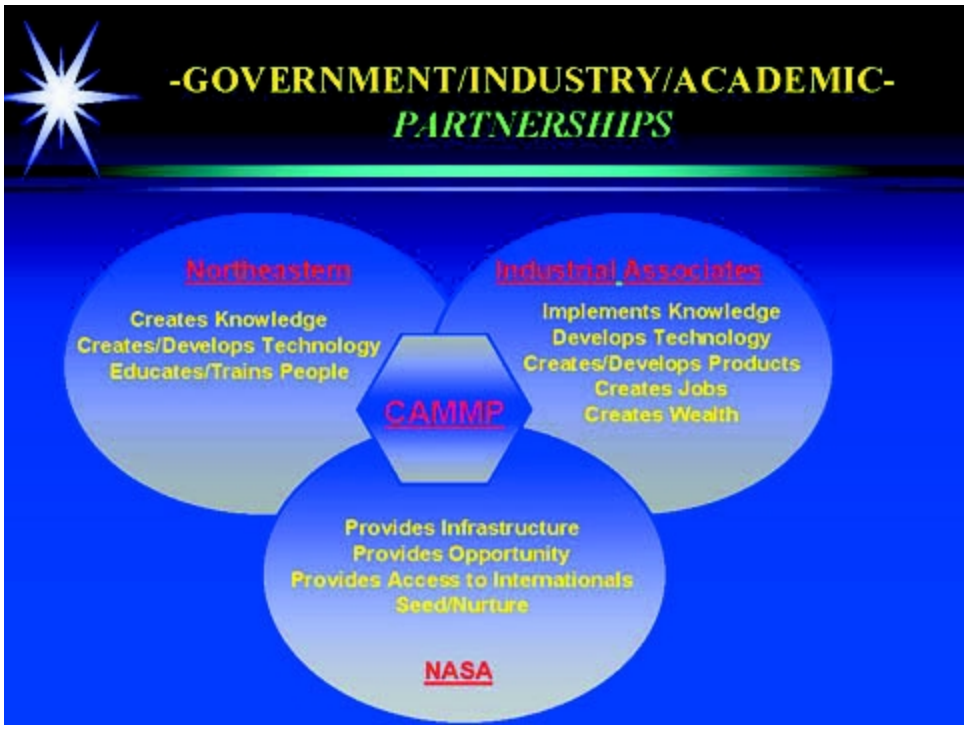


Figure 2. CAMMP's philosophy.

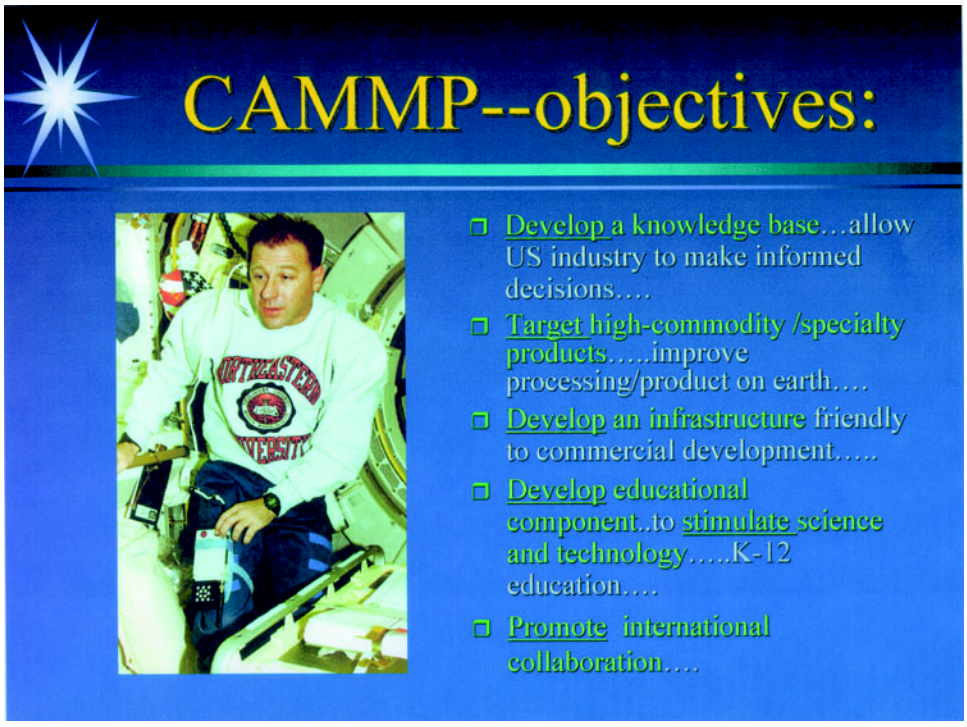


Figure 3. CAMMP's objectives.

There are many commercial space opportunities (Figure 4). The easy ones, I would claim to you, are transportation, communications, remote sensing. Those are all very obvious to us. The initial commercial activities will undoubtedly be in those areas. In order for those to be successful we are going to have to develop the more interesting and difficult ones, activities such as space resource harvesting, space agricul-

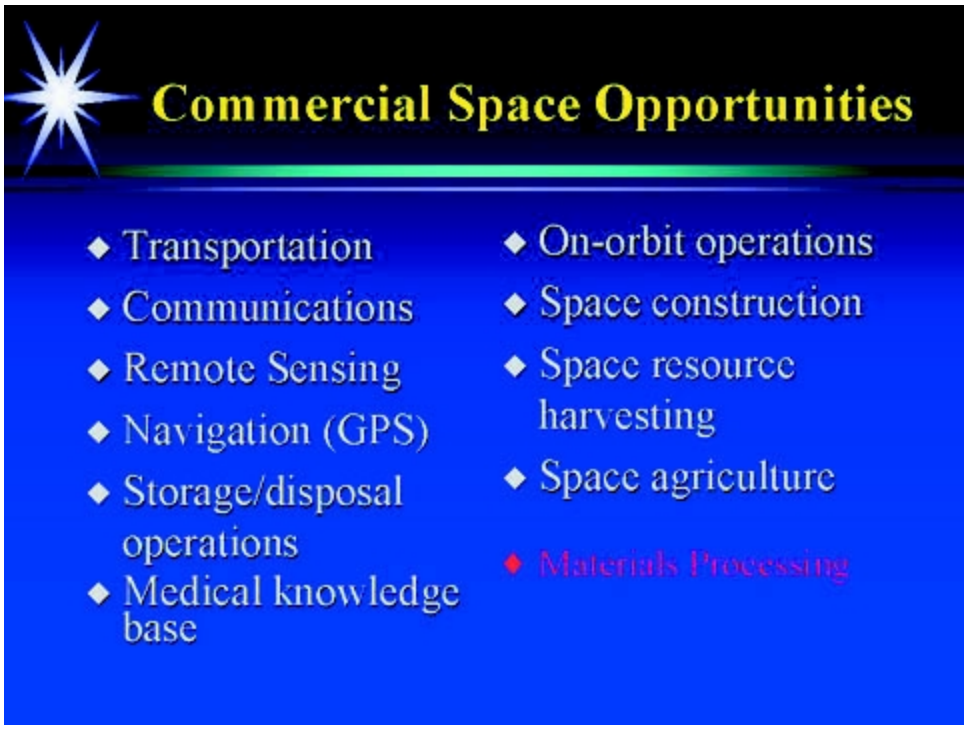


Figure 4. Commercial space opportunities.

ture, medical knowledge bases, and what I am going to talk about today, materials processing. Those are the markets of the future that are going to use this commercially developed infrastructure.

I come from the chemical process industry. I've done all my research in that area. There is a document that was put together by the industrial folks that the chemical process industries call "Vision 2020." (Figure 5)



Figure 5. "Vision 2020" from the chemical process industries.

Vision 2020 is what our industrial leaders, presently chief executive officers of all the major chemical and pharmaceutical companies in this country, feel is necessary in order to keep us globally competitive, that is, the U.S., and in the forefront in the chemical process industry. In the new chemical, sciences and engineering technologies they identify three areas: chemical synthesis, bioprocesses and biotechnology, and materials technology. The real question we have as we look into our crystal ball is whether or not we can take advantage of space and low Earth orbit to advance those areas, to keep ourselves globally competitive.

Presently there is a lot of preliminary work that has been done. On my flight alone there were a number of activities that were supported in part by industrial activities (Figure 6). They cover a wide variety of different materials you've heard about today, but I'm going to talk about zeolites. In order to talk about zeolites, you ought to know what one is.



Figure 6. Industrial flight activities.

We will first talk about why we should grow them (Figure 7). The scientific rationale is they are twice as dense as the solutions in which they are formed. So we really are going to eliminate sedimentation, get diffusion-limited growth, and eliminate secondary nucleation effects. What that is going to allow us to do is what is called in our industry, defect control. Defects are catalytically active sites. We want them in some cases but we want them in certain positions.

There is the economic rationale, as I mentioned before. Zeolites are the chemical process industry's major catalytic material. There are a lot of exotic uses; ambient storage of hydrogen is one; high speed optical switches is another. To give you an idea of why they are useful for industry, this is just a very quick chart (Figure 8). It's a plot of percentage of pore openings in a crystal versus diameter in angstroms. Zeolite A has very uniform pore structure, and if I want to pull out a molecule from a bunch of other molecules, which is what you do in the industry, and do something to that molecule, then one needs to be molecularly selective. So it's a way to molecular engineer. If you look at silica gels, they have a much broader distribu-

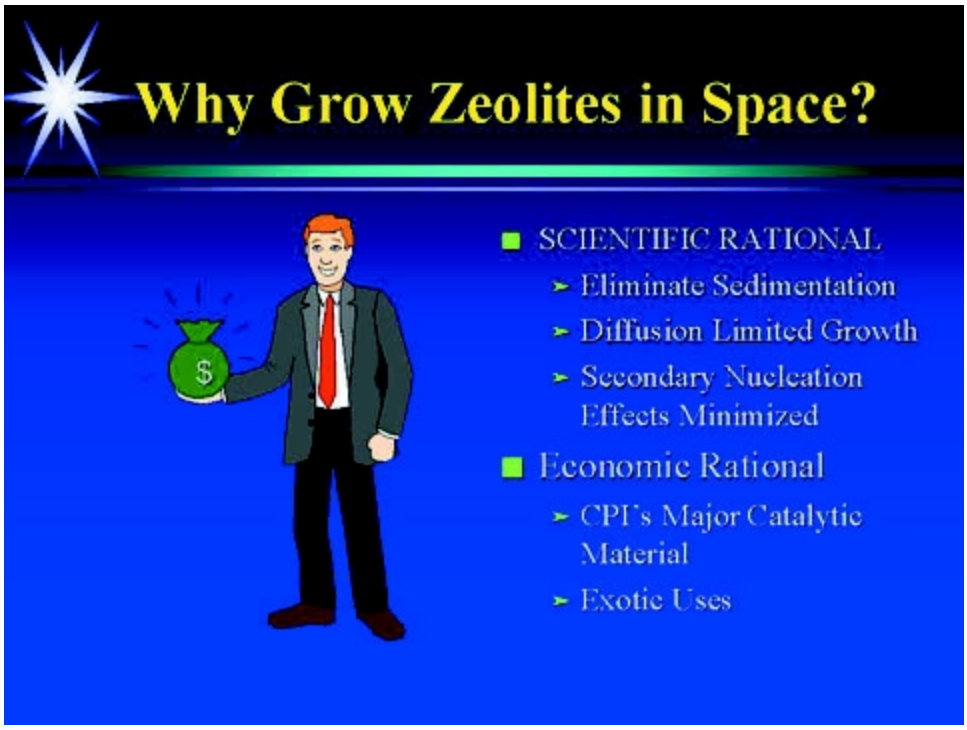


Figure 7. Rationale for growing zeolites.

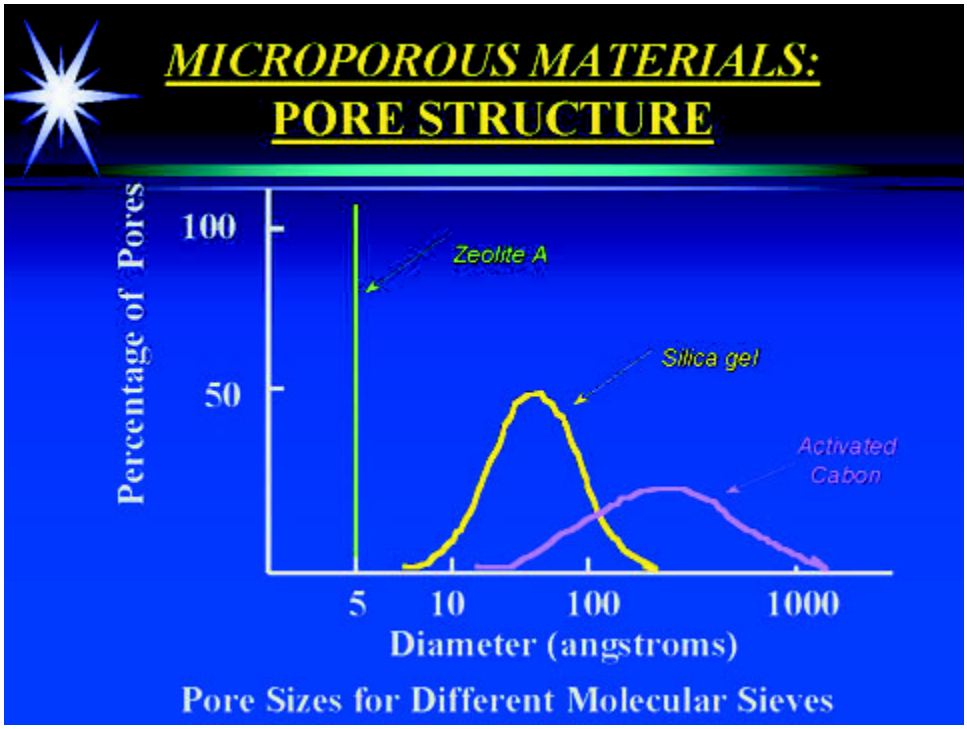


Figure 8. Zeolite porosity.

tion, which means you can't be molecularly selective, and of course carbon is the universal absorbent; it picks up everything. That's not very useful at all. So the real reason we use zeolites is because we can pull out one molecule. Then once we get hold of it, we can do something with it.

Now for the industrial importance (Figure 9). Zeolites are a $2 billion a year business. Those business areas are in specialties and catalysis; we won't talk about natural absorption (a large interest area) today. What we are going to talk about today, what I'm going to show you is some potential impacts on catalysis area and specialties as well as absorbent.

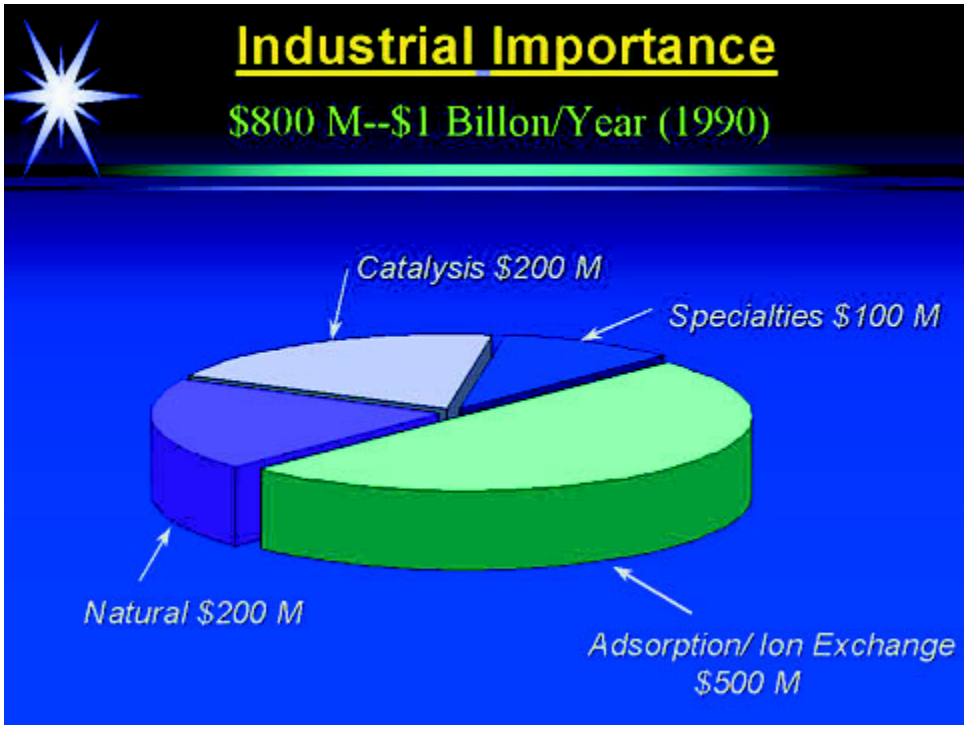


Figure 9. Zeolite industrial importance.

The growth of zeolites has been enormous. The market is well over $2 billion annually (Figure 10). But the real impact is illustrated in these National Research Council documents. Since their introduction in the 1960s, zeolites have saved 60 percent of the total oil production from Alaska's North Slope, meaning they were able to get more production from a barrel of gasoline, which is why Alaska's North Slope, Prudhoe Bay, Kopecnik and those areas are still functioning (Figure 11). They are still producing because we can get much more gasoline per barrel. A one percent increase in the yield of gasoline from oil would represent a $400 million swing in the U.S. balance of payments. That's not my data; that's from the National Research Council reports. So selectivity, which impacts yield, is what we are going to show you later on, how space seems to affect that, and why the chemical process industry is getting very excited about some preliminary results.

Zeolites have different size pores, and so we can molecularly select different things. Basically they have different structures (Figure 12). About 50 are known, and crystallographers tell us that's probably less than five percent of the structures that can form (Figure 13). That's another big area for us. The larger structures have a tendency to collapse before we can stabilize them. So the question is, can we grow zeolites in orbit and try to stabilize them in orbit? That's what folks in companies like Exxon have asked me. I'm not so sure that can be done, but they're very interested in that.

Just to give you an idea of how zeolites are formed, you take a solution, primarily water and mix it together (Figure 14). You form a nutrient pool, shown here in the gray area, and those zeolites begin to form from

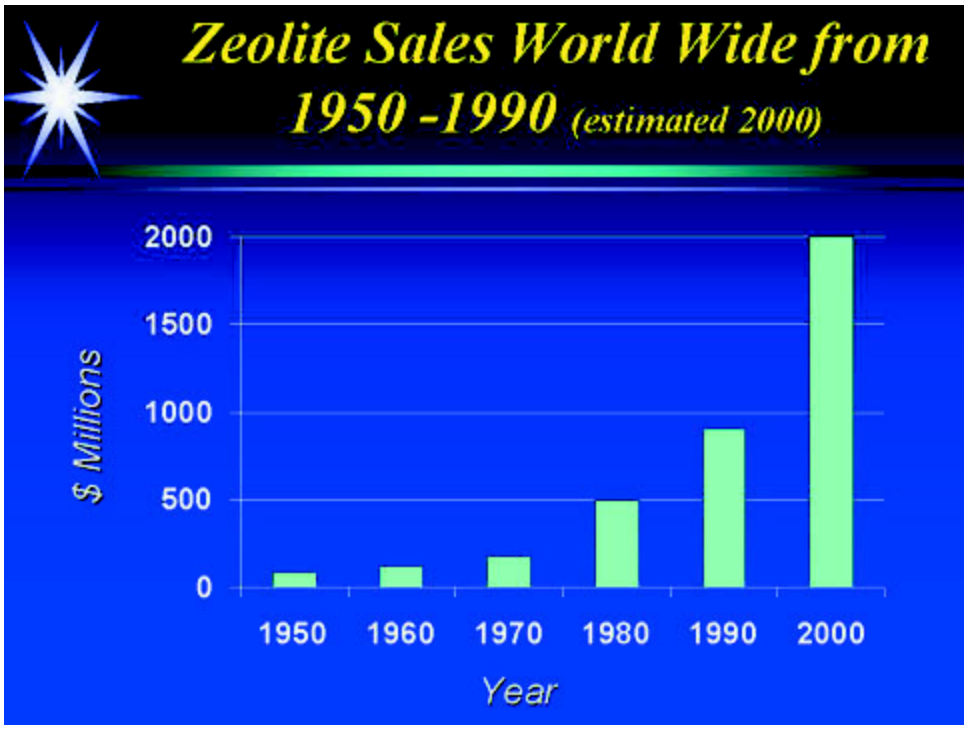


Figure 10. Zeolite market importance.

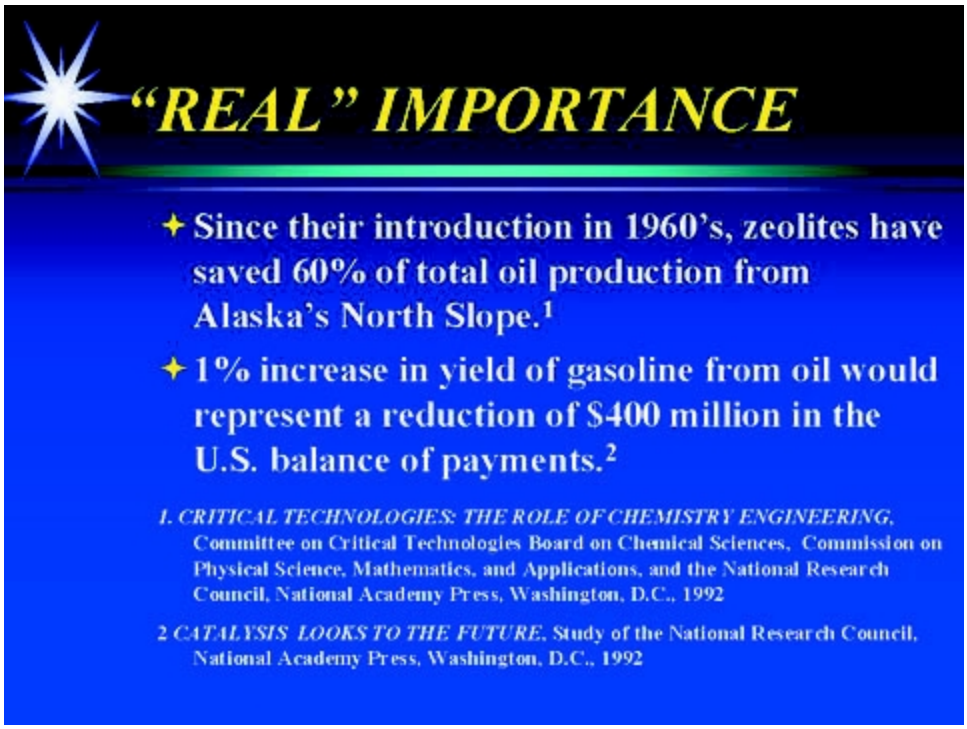


Figure 11. Zeolite industrial uses.

that nutrient pool at the end of which all you have are crystals and no nutrient pool. We need to mix in orbit. I'll show you data that supports that conclusion in a minute. We need to control or slow down the nucleation event in order to be able to do some of this defect controlling and size controlling, and we need

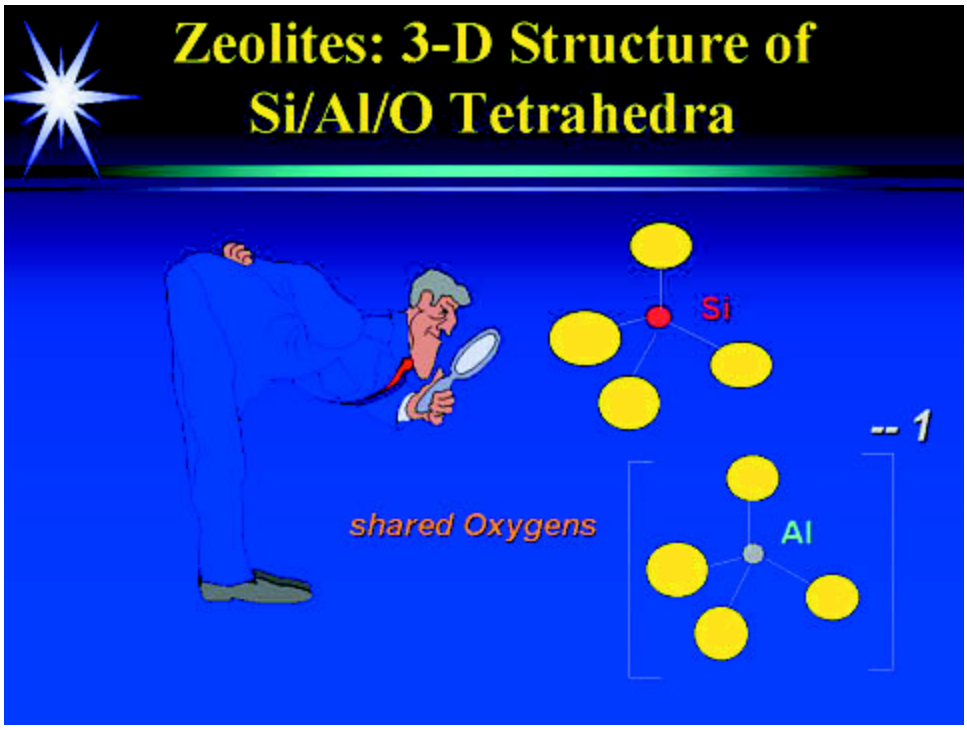


Figure 12. Zeolite structures.

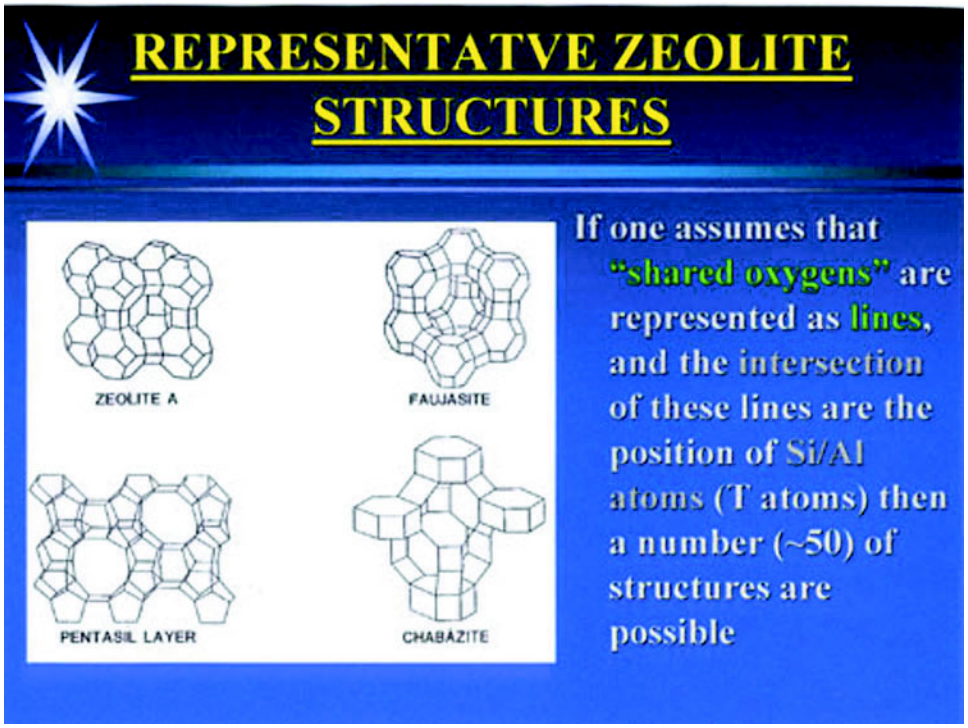


Figure 13. Known zeolite forms.

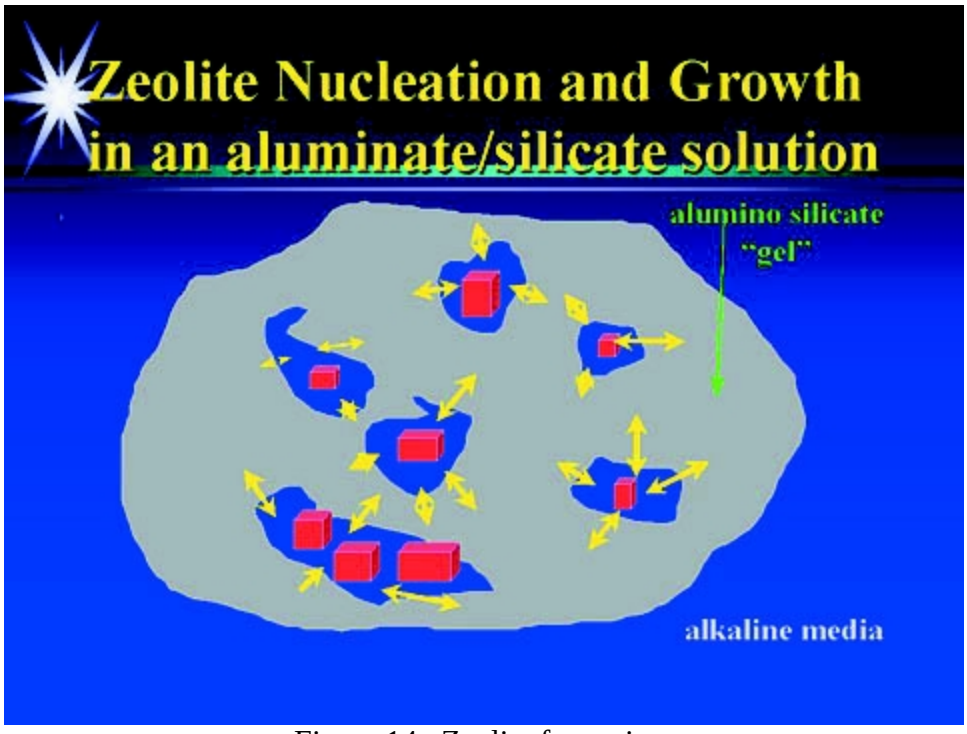


Figure 14. Zeolite formation.

minimal vibration. So, space seemed like an obvious area or laboratory that we could use, perhaps to our benefit (Figure 15).

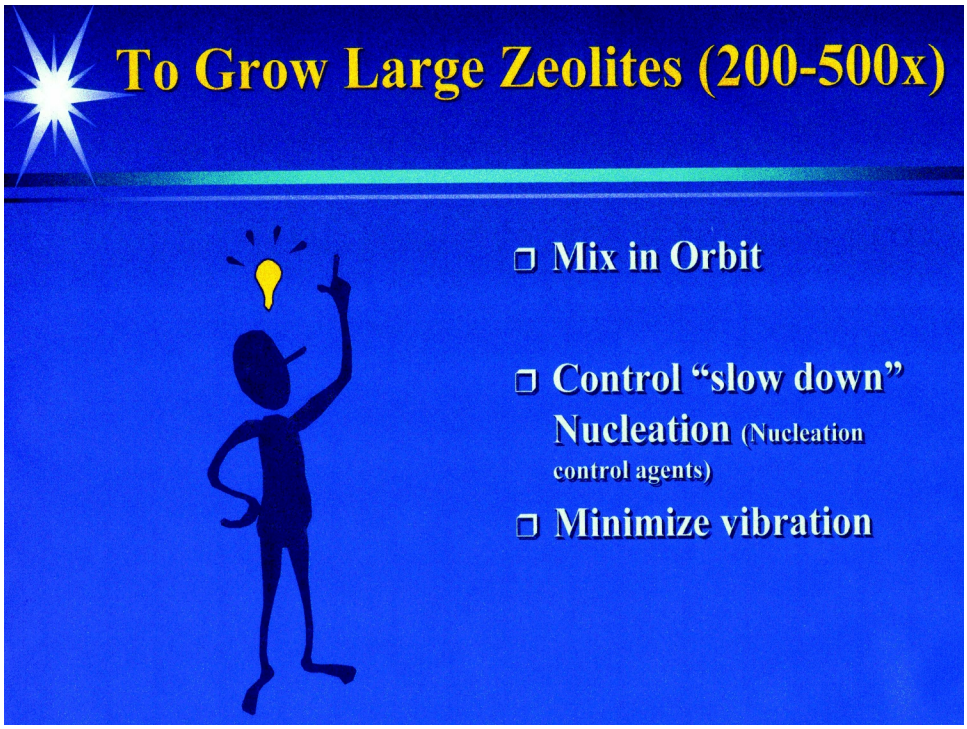


Figure 15. Use of microgravity for zeolite formation.

About 90 percent of my research dollars always came from a continuous program with the National Science Foundation. When I decided to get into space, I decided to get involved with NASA through what is called the Get-Away-Special (GAS) program. In fact, Joel Kearns was a student with us at that time and he was involved with some of this activity developing this gas can. This work was industrially supported; it didn't come from any government agency.

We wanted to look at zeolite formation in space. We pre-mix our zeolites, which is what you had to do in the gas can program. It sat on the pad for 120 days. It looked like everything was stable and great, and we went to orbit. What did we see? These are zeolite crystals from the flight, and these are zeolite crystals from terrestrial control (Figure 16). As you can see, there is no difference at all. There wasn't a warm

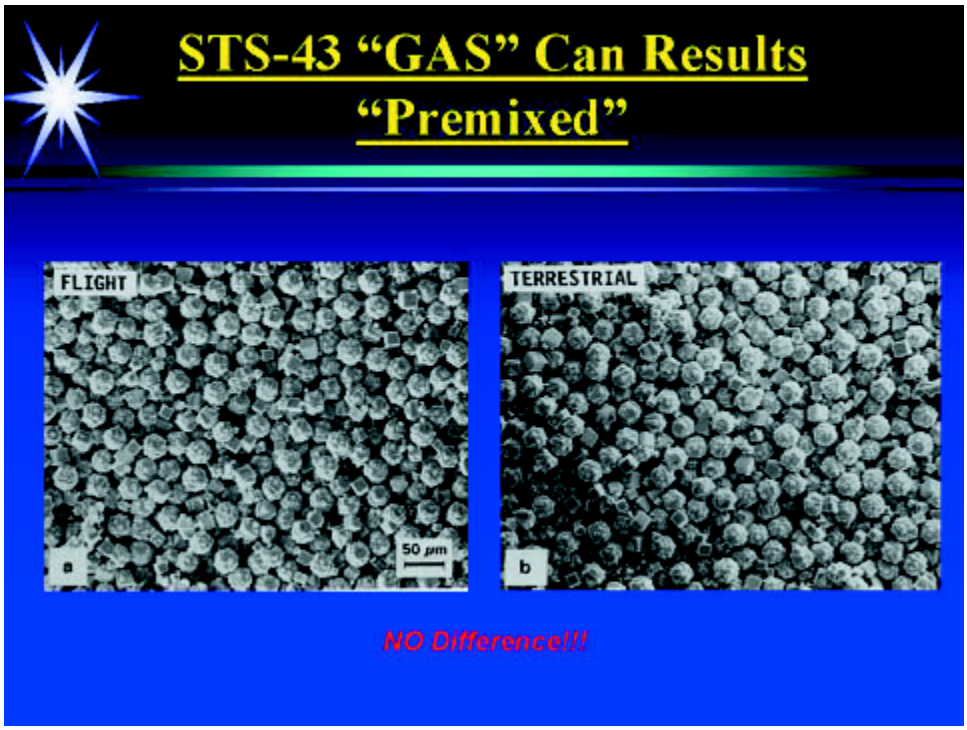


Figure 16. Comparison of zeolites formed in flight and on the ground.

feeling in my heart about this. Nevertheless, if you look real closely, you will see that what should be perfect cubes, are not. They are intergrown. Up to that time people had not realized exactly when the nucleation event occurred. We went to NIST, to the beam line, and we found out that as soon as these solutions came in contact things began to happen. The truth of this experiment was that everything was over in that 120-day pre-mission loading before we launched. So the process was already completed, and that's why they look the same.

We built a furnace to be able to mix on orbit. Another thing that happens commercially is we are able to build things much cheaper and in a timely way. You see the specifications for it (Figure 17). This furnace was built within 18 months from the time it was authorized; from the time we came up with idea we were going to fly, 18 months later we were on the orbiter processing on USML-1, and it cost about $2.7 million, which by flight equipment standards, those of you who develop them, know that is pretty quick and that is pretty cheap. We've flown it three times. We've never had an abnormality with it. That was an integrated group between scientists, development people and NASA. It was a real interesting thing. It allowed us to



Figure 17. Zeolite furnace specifications.

mix on orbit. This is what we found when we mixed on orbit (Figure 18). We also used a compound called triethanolamine to try to control the nucleation event. There's our ground-based controls and there is what we got on USML-2, the flight I was on. There is a particle size distribution to show you it was not perfect, but we did get very much larger crystals.

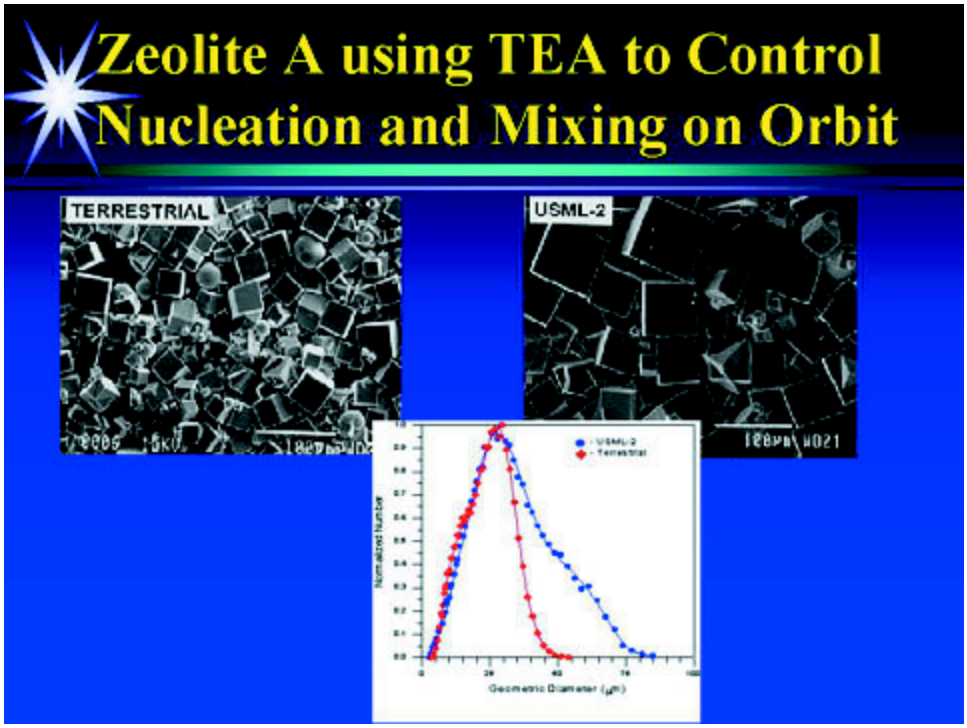


Figure 18. Zeolite formation with on-orbit mixing.

If we look at the zeolites with AFM you see a much smoother surface on the space grown zeolites than on the terrestrial grown (Figure 19). In fact, that is a two micron cross section. If we go up to about 5,000 angstroms across, we can see the growth planes. From that we can begin to get an idea of how these crystals grow. At the time we had done this, this was new also. It has now been pretty much confirmed and it has been published.

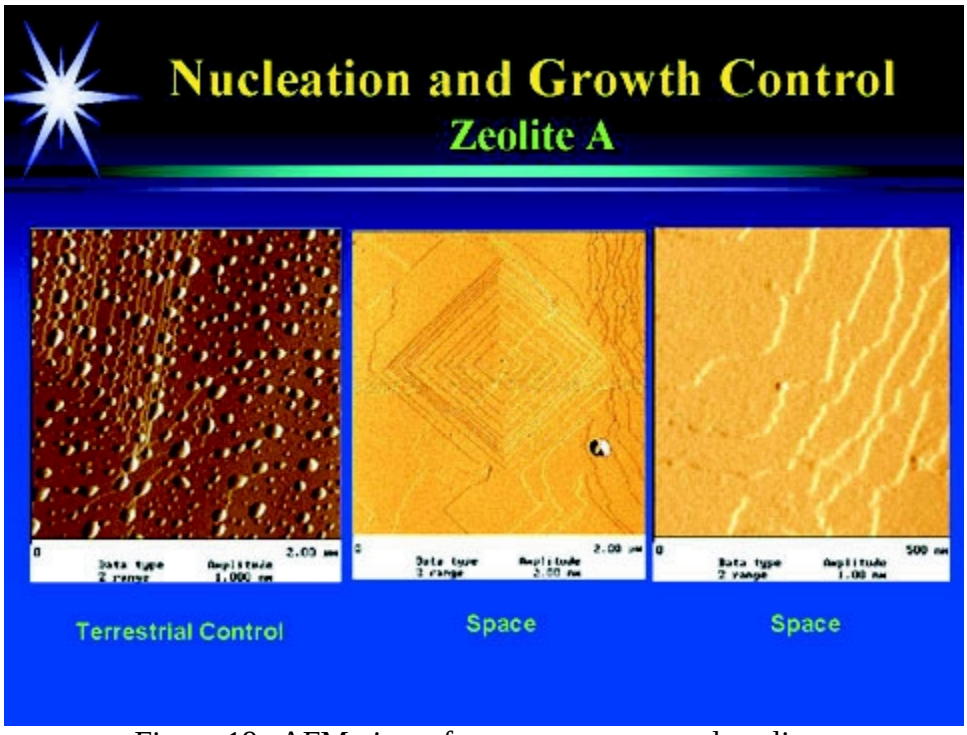


Figure 19. AFM view of space versus ground zeolites.

We do sectional analysis (Figure 20, Figure 21). Basically it says that we are much smoother in orbit, the outside of the crystal. We are able to use different nucleation control agents. We've learned now how to

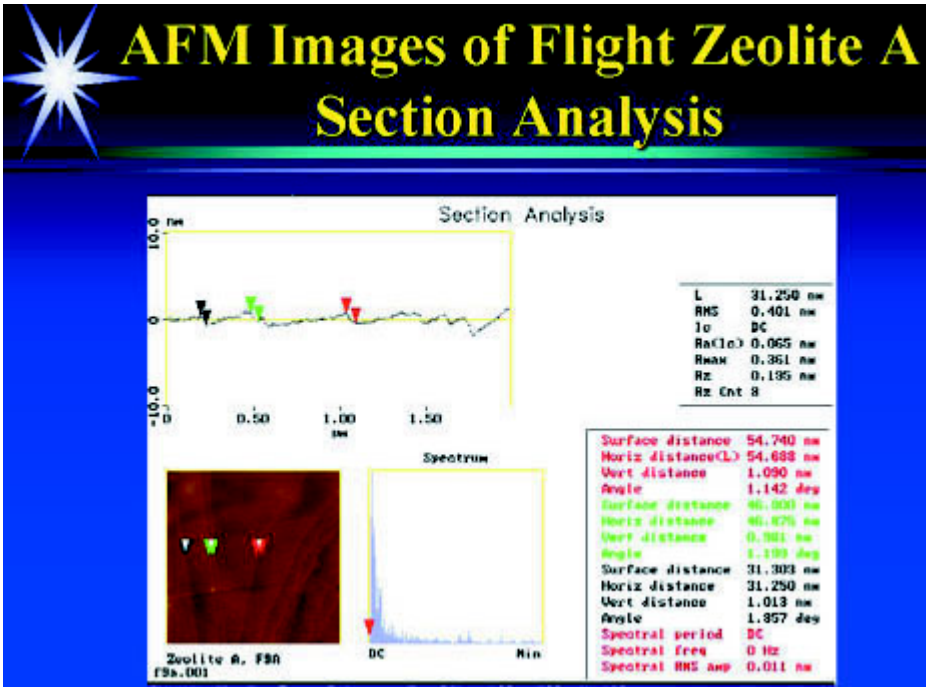


Figure 20. Sectional analysis of zeolites.

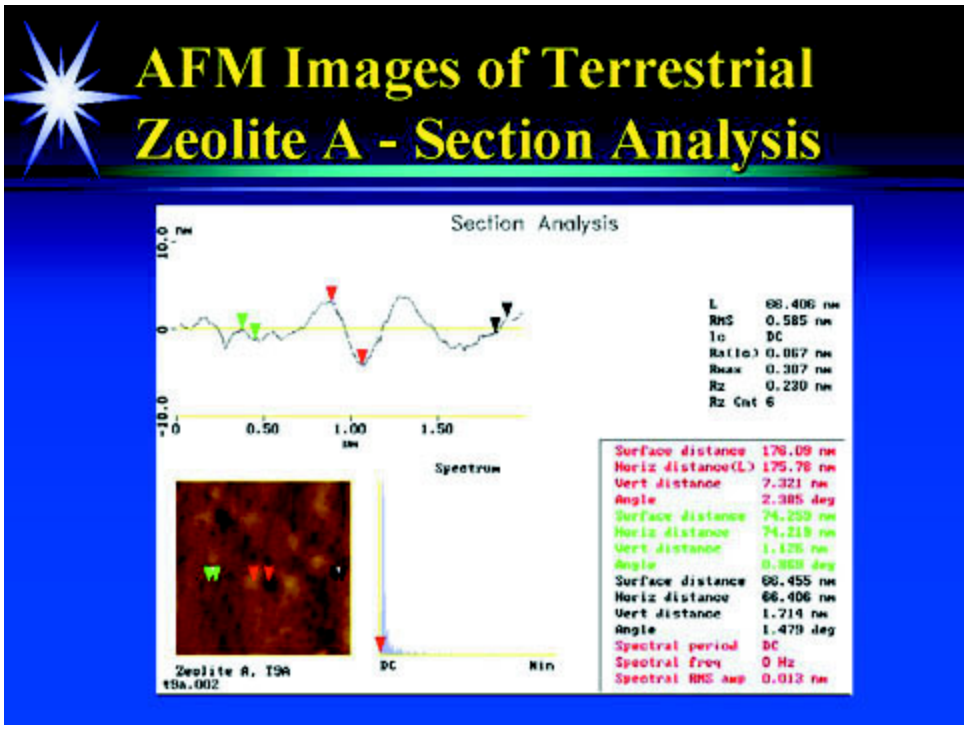


Figure 21. Sectional analysis of zeolites.

control that nucleation by forming a clathrate structure using basically a shift in equilibrium between that clathrate and the solution. This is a sample that we didn't even finish processing in 16 days, and we would have separated these two curves, the red being the terrestrial and the blue being the space crystals, to a much greater extent if processing time was longer (Figure 22).

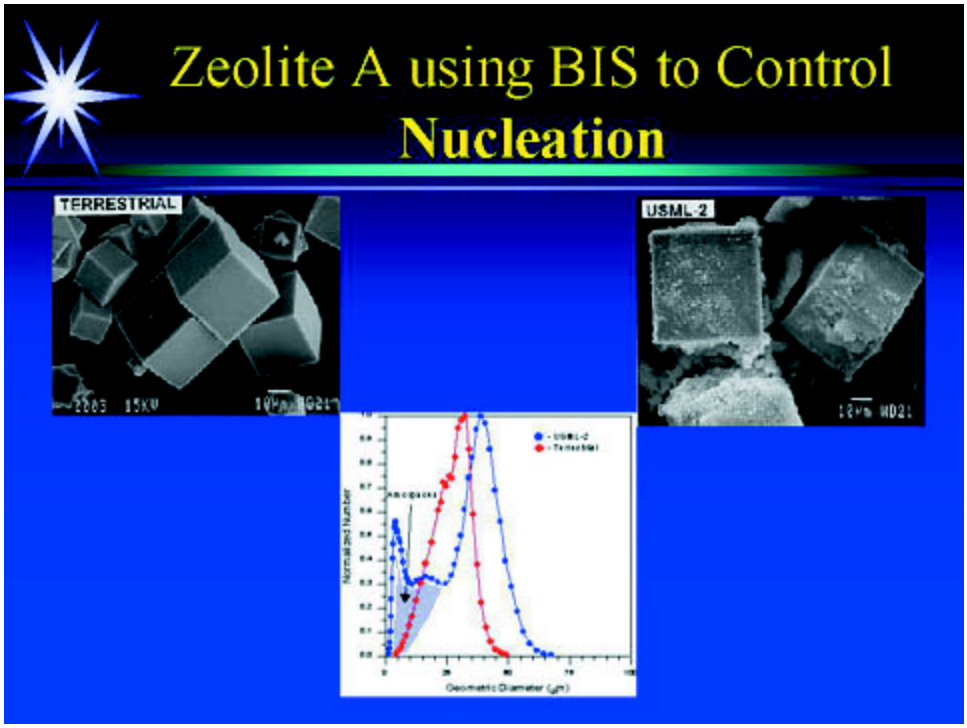


Figure 22. Nucleation differences, flight and ground.

So we now can control the size of the crystal, to larger sizes. Now one of the things we are interested in doing is controlling the defect concentration. We can control, to a limited extent, the defect concentration. We are now trying to go to submicron size crystals.

This gives you an idea, based on a volume average, of a normalized result (Figure 23). By controlling the nucleation both on the ground and in space, we get enhancement of the growth, and reduce the number of nuclei formed. If you look at the right-hand column, basically it says you get 35 percent reduction for formulation 2. The formulations are really not that important; they were randomly chosen. Between 14 and 39 percent reduction for formulation 3, and 26 percent reduction in the number of nuclei for formulation 4. That's why we grow them larger. We get fewer nuclei; they are in a fixed volume; they grow larger. Pretty simple.

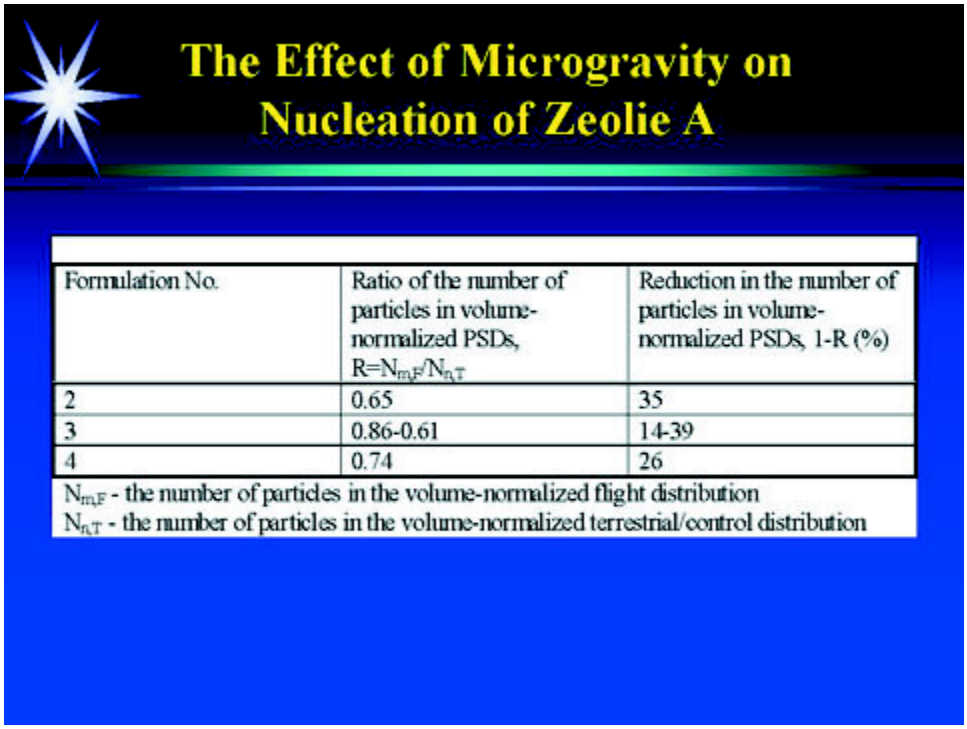


Figure 23. Normalized growth results.

One of the things that we saw, and this is consistent with zeolite A, and it's also consistent with most of our other zeolites, is that we always ended up getting a smaller lattice parameter, a smaller volume (Figure 24). That's indicative of fewer lattice defects in the crystal.

Zeolite A is pretty easy to form. It is very well formed on the ground. Zeolite A was our toughest test, and there was still a difference. If we look at a single crystal, and this happens to be 200 plane, you see flight A crystals versus what you get from the terrestrial A crystals, which look as nice, but they obviously have a lot more defects in them even for someone that is not used to looking at this (Figure 25). What is important to look at is the intensity. If it is very well formed crystals, the intensity should all be the same. This is what we get between a commercial zeolite A formulation and what we are able to do on USML-2 (Figure 26).

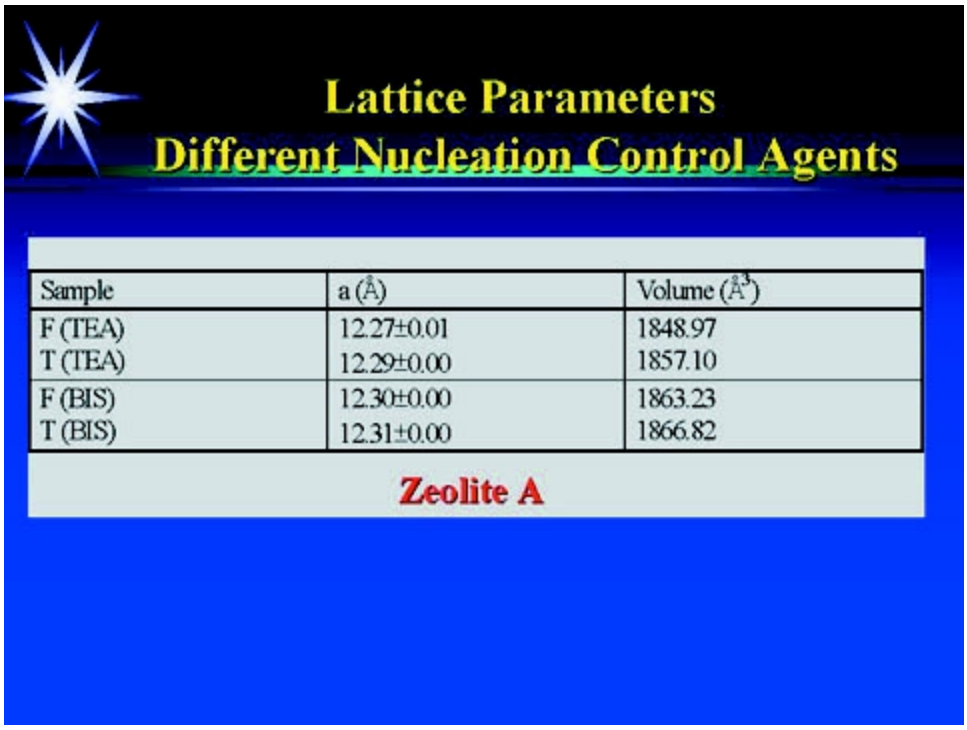


Figure 24. Zeolite A.

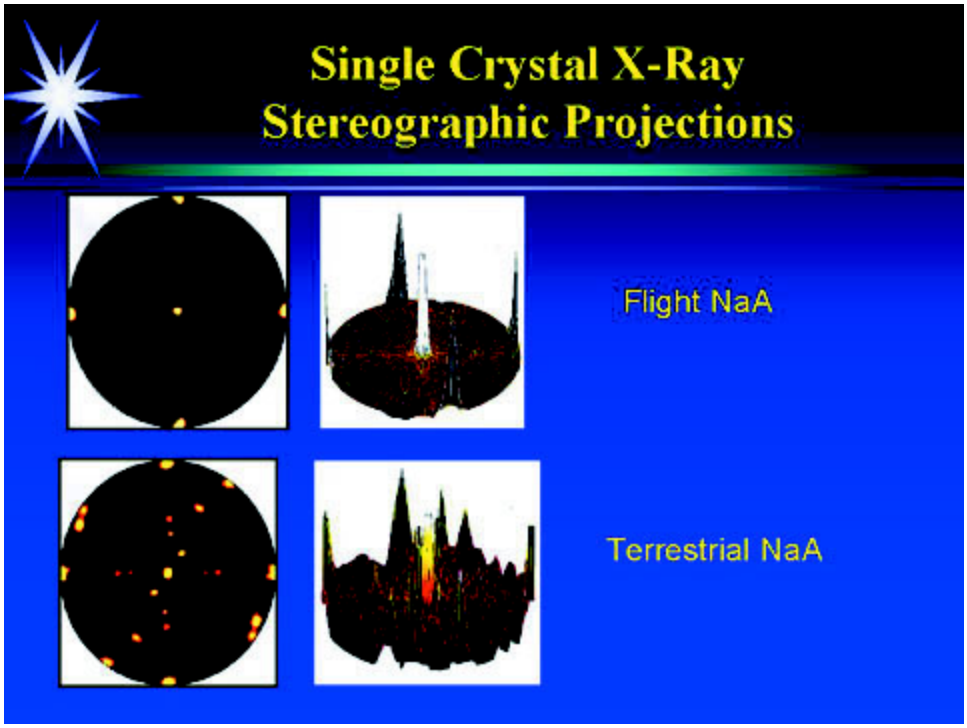


Figure 25. Flight versus ground Zeolite A crystals.

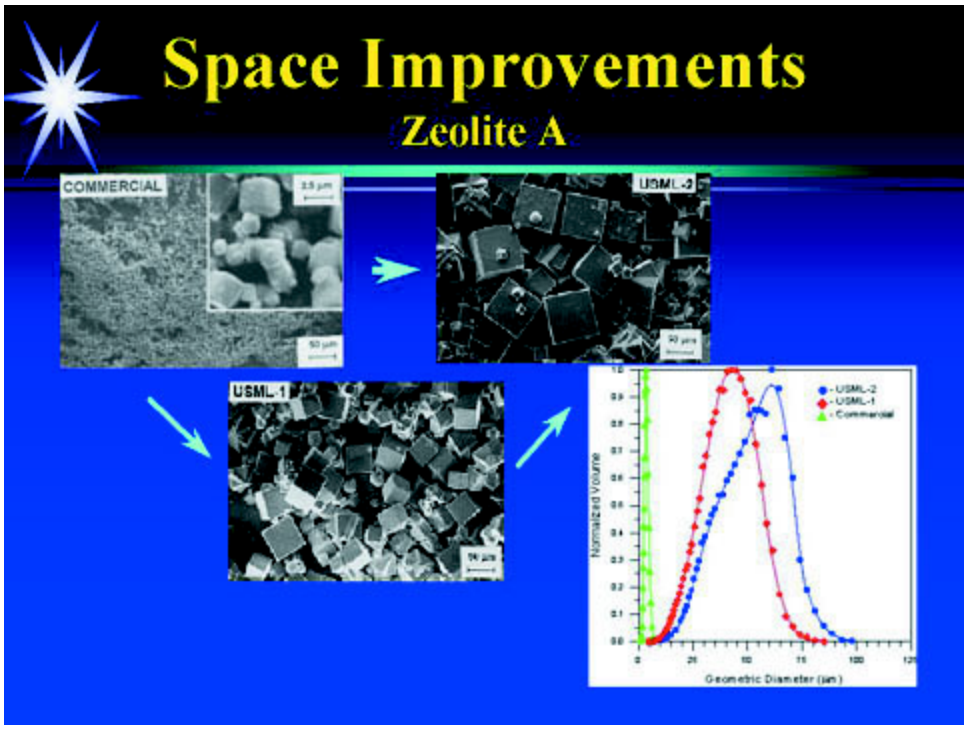


Figure 26. Zeolite A, flight versus ground growth, USML-2.

Here is USML-1. We are now able to duplicate the USML-1 results based on what we found from our space processing experience, which by the way has been four flights (Figure 27).

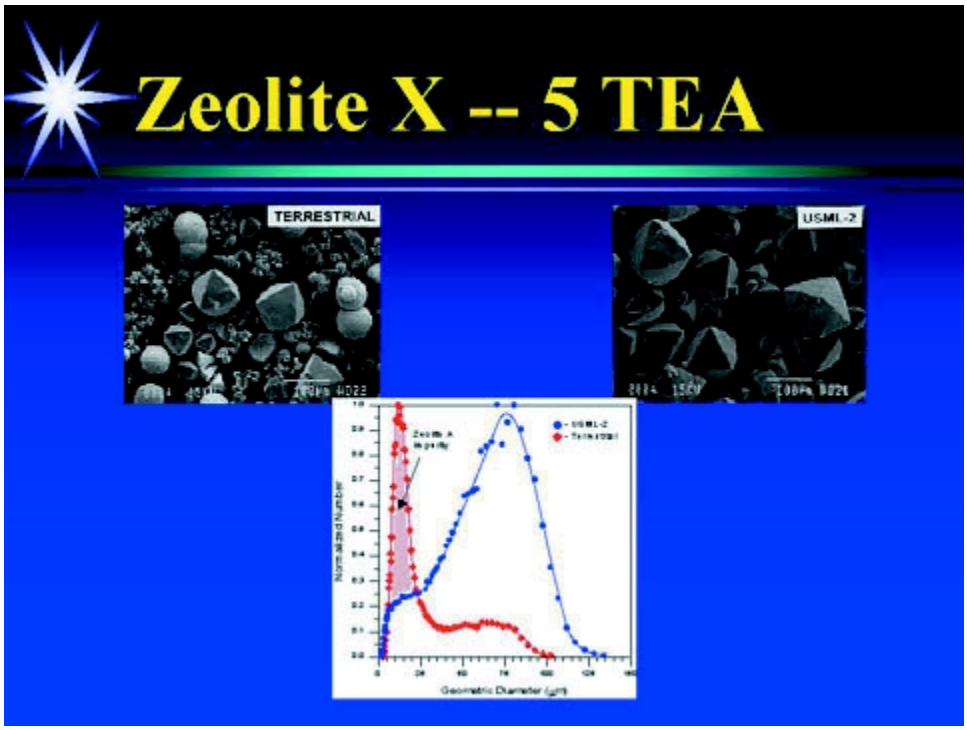


Figure 27. Zeolite A, flight versus ground growth, USML-1.

X is a more industrially significant zeolite (Figure 28). We were able to do better things with that. It's more complicated. As you see, the size difference is larger, which translates into having more control over the nucleation event.

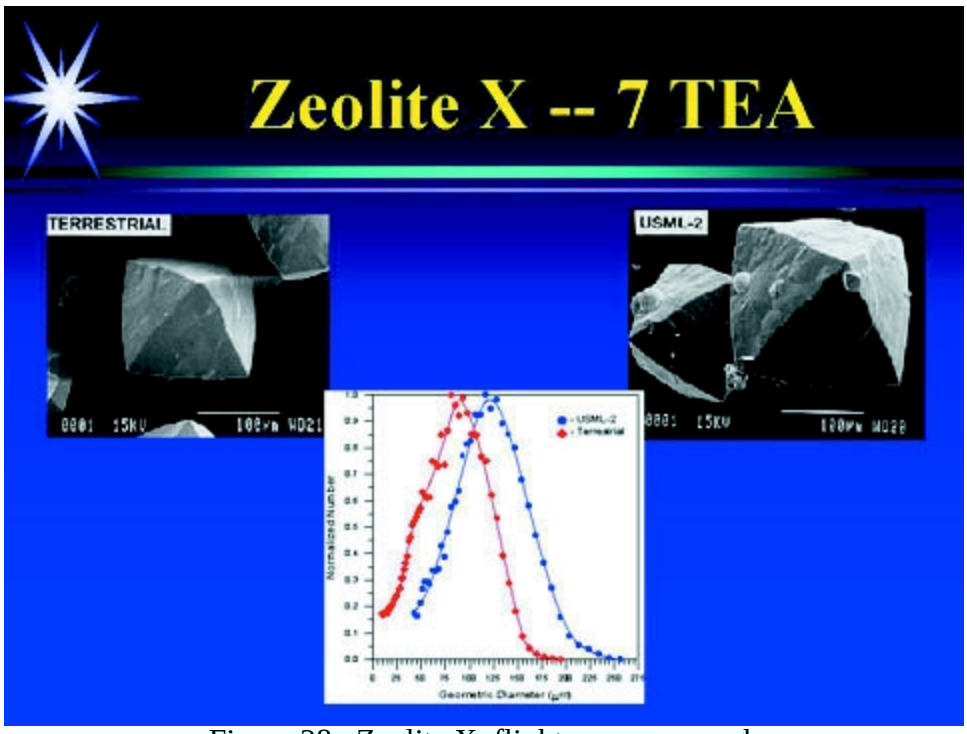


Figure 28. Zeolite X, flight versus ground.

We can play around with our nucleation control agent and shift it up to very, very high particle sizes, in the range of 300 microns, which was the size the physicists told us they needed for quantum dots for occlusion of semiconductors into these materials in order to be able to look at optical switches. That is what we are in the process of doing with these large zeolite crystals.

We also saw that if we look at cross sections, the silicate-alumina ratio was always higher in the space crystals (Figure 29). That is true no matter what we have. That says something about how the aluminum atoms are surrounded, and the aluminum atoms in the chemical process industry are the important ones. Those are the atoms that are associated with the catalysis. What they are surrounded with gives us an indication of how many active sites are in a general vicinity, the concentration of active sites, and that impacts that third slide I showed you on selectivity.

Same kind of images (Figure 30). We get a much smoother surface, terrestrial and flight. This is consistent in all our results. That has to do with the selectivity as well, because the OH concentration on a smoother surface is significantly less. This is sort of general size difference. There is a very big difference for zeolite X, between that and what we get commercially.

This is what I got on the first space flight (Figure 31). We are still not able to duplicate that, but we are getting close to it. You also notice the morphological differences of diffusion-limited growth. You end up with a much more uniform morphology than shown in that insert.

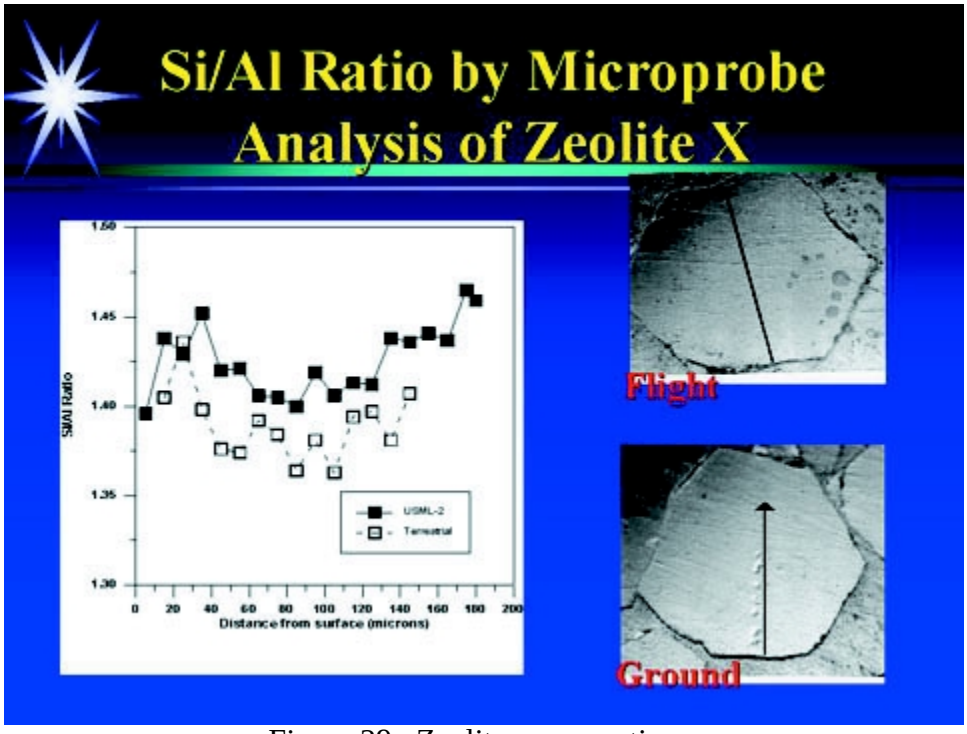


Figure 29. Zeolite cross sections.

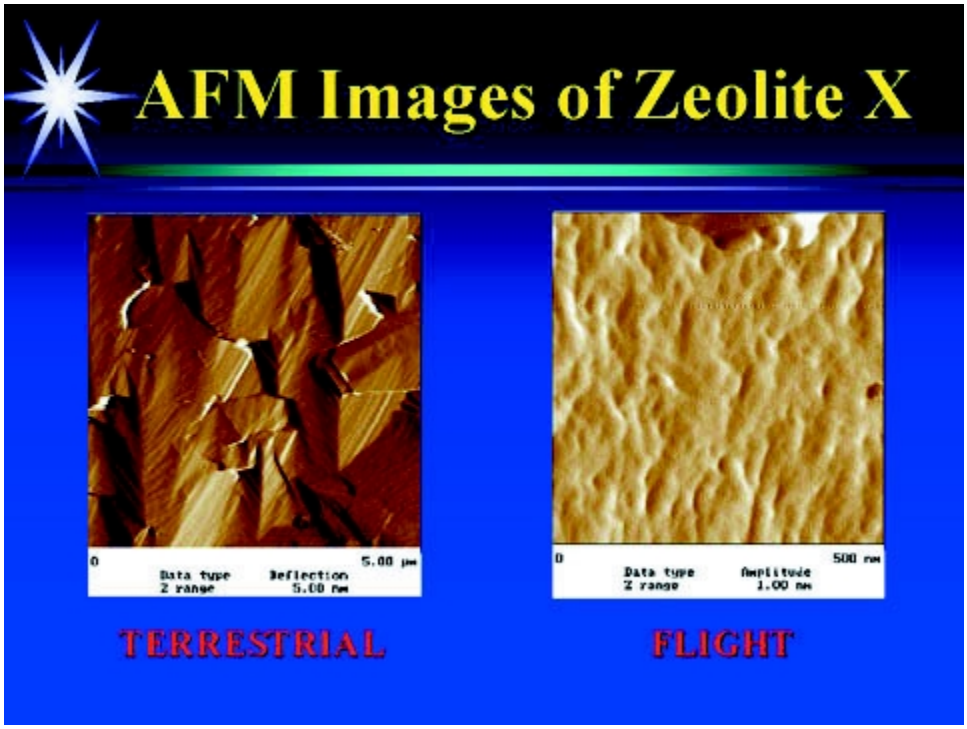


Figure 30. Zeolite X cross sections, flight versus ground.

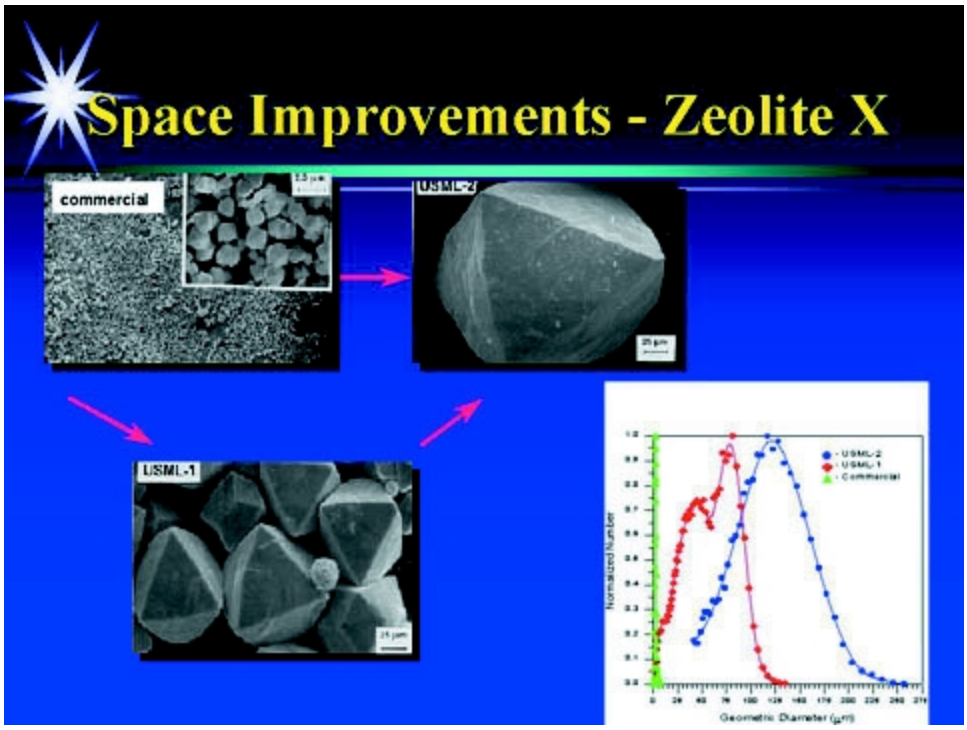


Figure 31. Initial space flight results.

Again, our serial projections here (Figure 32). This is Flight X. The circles are a little bit larger that you see there — this is the 111 surface — compared to our ground-based control. The reason for that is believed to be "tension" in the outer layers of the X crystal. We're not sure why that is, but it is only on the outer surface.

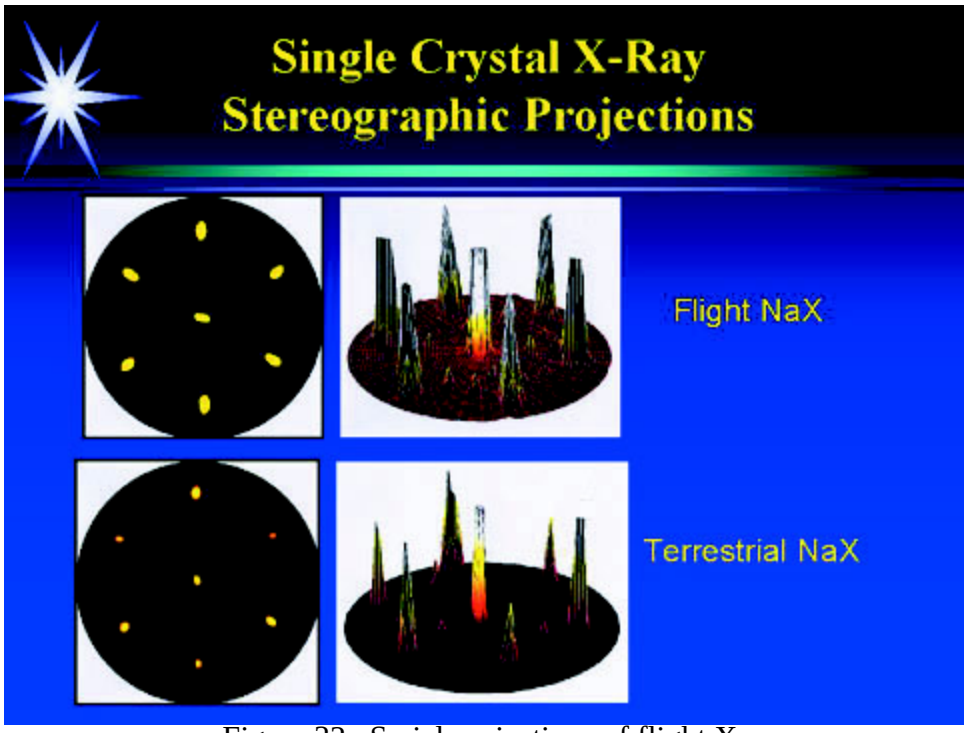


Figure 32. Serial projections of flight X.

If we basically look inside, this is the same crystal (Figure 33). We go from the 111 to the 222 to the 333. You see what they call pole piece projections or projections down a zone axis, indicating very few if any structural defects within the crystal. When we compare that to the ground-based X, you will see a substantial difference. This is what is getting people excited, because it means we now have a range of almost no defects to many defects. Unlike protein crystal growth and electronic materials, what we really want in the chemical process industry is to do defect engineering; we want those defects in certain locations. So now we know we have the limits, and we can control it by controlling the fluid dynamics.

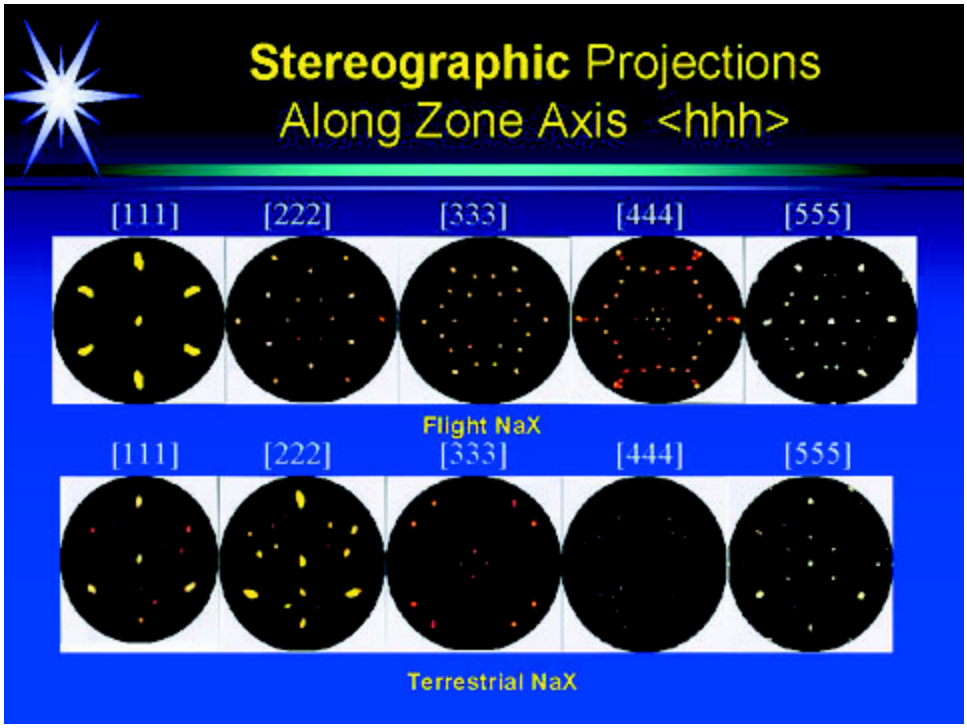


Figure 33. Serial projections of flight and ground X.

As we get to more complicated systems interesting things happen (Figure 34). This is silicalite, a very interesting material. What we found is completely different morphologies in space. The morphology on the right-hand side can be duplicated on the ground, we now found out by doing a lot of slowing down of things. This was the first indication. It's 100 percent silicalite in both cases. It's just that the morphology is a lot different.

Interestingly, if we look at the two surfaces (Figure 35), we see a very rough surface in the terrestrial one, very smooth on USML-2, consistent with all the other results we've got, but if we begin to look at atomic levels (Figure 36), one finds what you would expect; you begin to see that they are very similar. Which means that some of the catalysis we are interested in depends on the size of the molecule and what surface areas and planes they are using. Of course there are a lot more active sites because it's a rougher surface on the ground-based one, and a lot less active sites on the space ones, even though if you get to the atomic level there is more. That's because you get a lot of intergrown crystals.

So we started looking at what they call probe reactions, which is really what industry is interested in. This is a probe reaction for looking at weakly acidic silenol groups. On the outside it's a C-C bond migration.

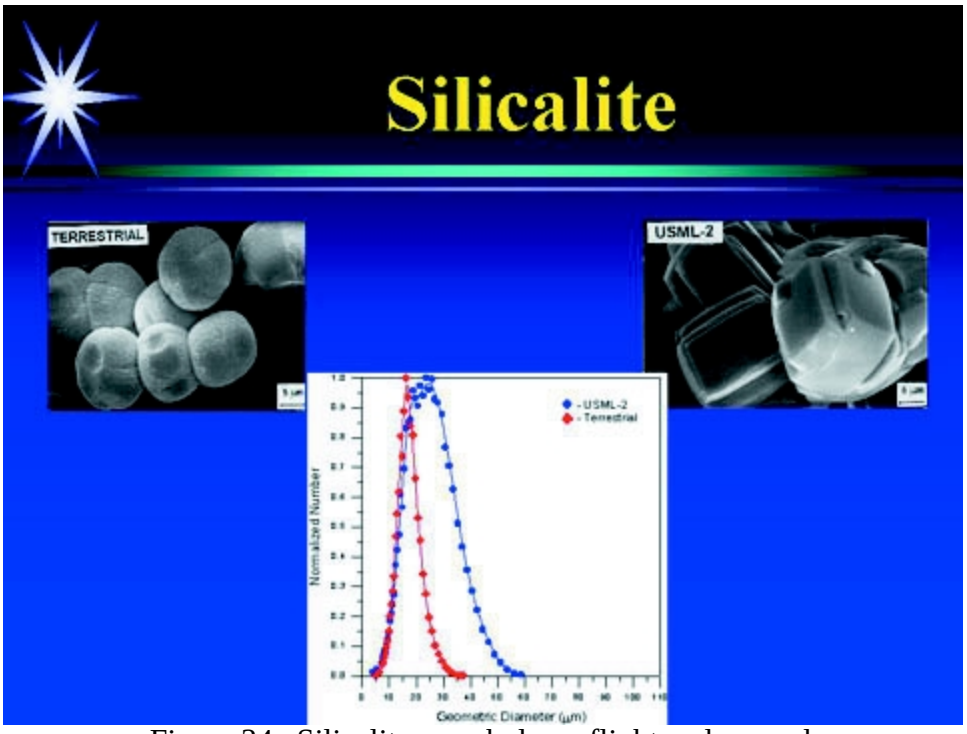


Figure 34. Silicalite morphology, flight and ground.

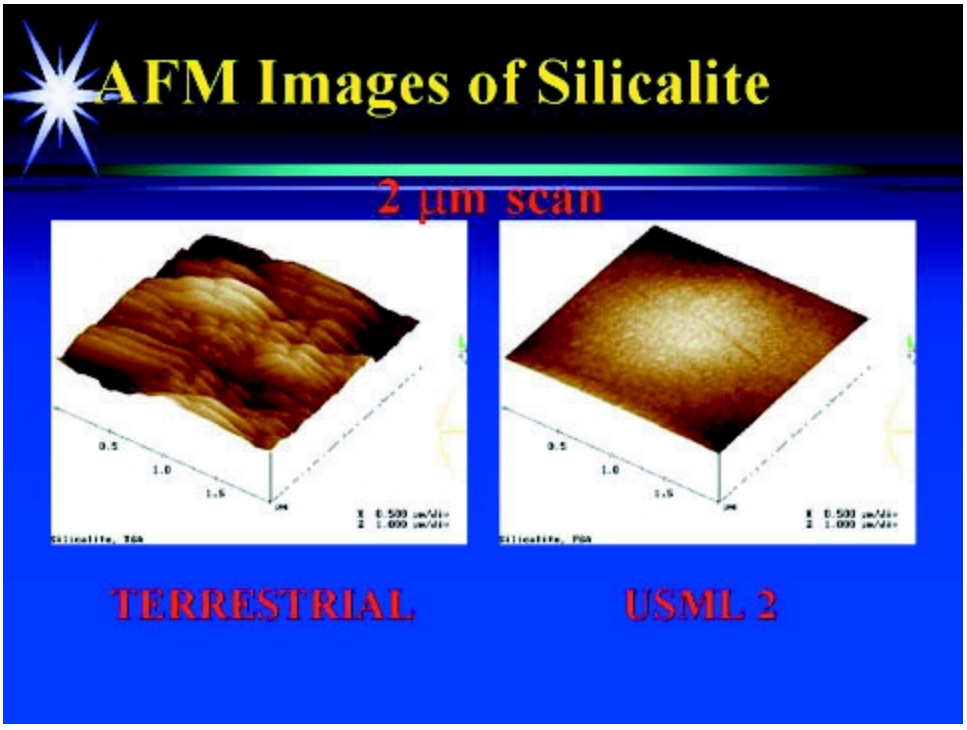


Figure 35. Silicalite surfaces, flight and ground.

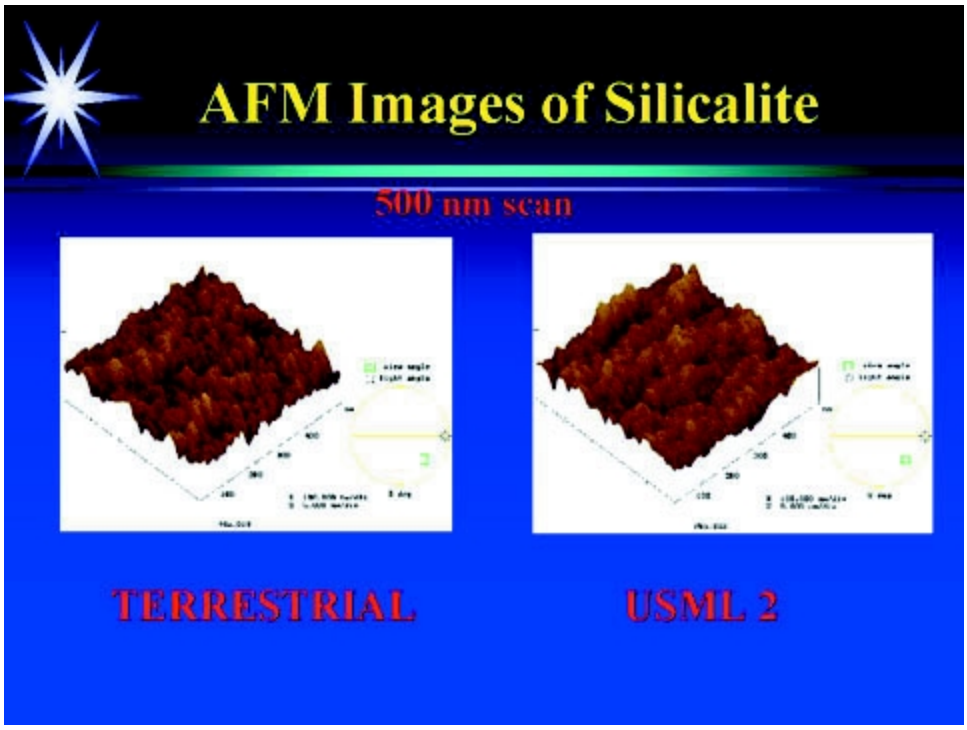


Figure 36. Atomic level comparison of silicalite.

That's not important. What is important is the results (Figure 37). This is on the external surface (Figure 38). What you see is a significant difference. Ground-based are less active because they have fewer active sites. People say, well, is that good? Yes, that's good, because if you have too many active [sites] in an area, you end up not with the selectivity that you want; you end up producing a lot of other things which drives the pollution problem in this country and worldwide. So now we want to be able to control that within those limits.

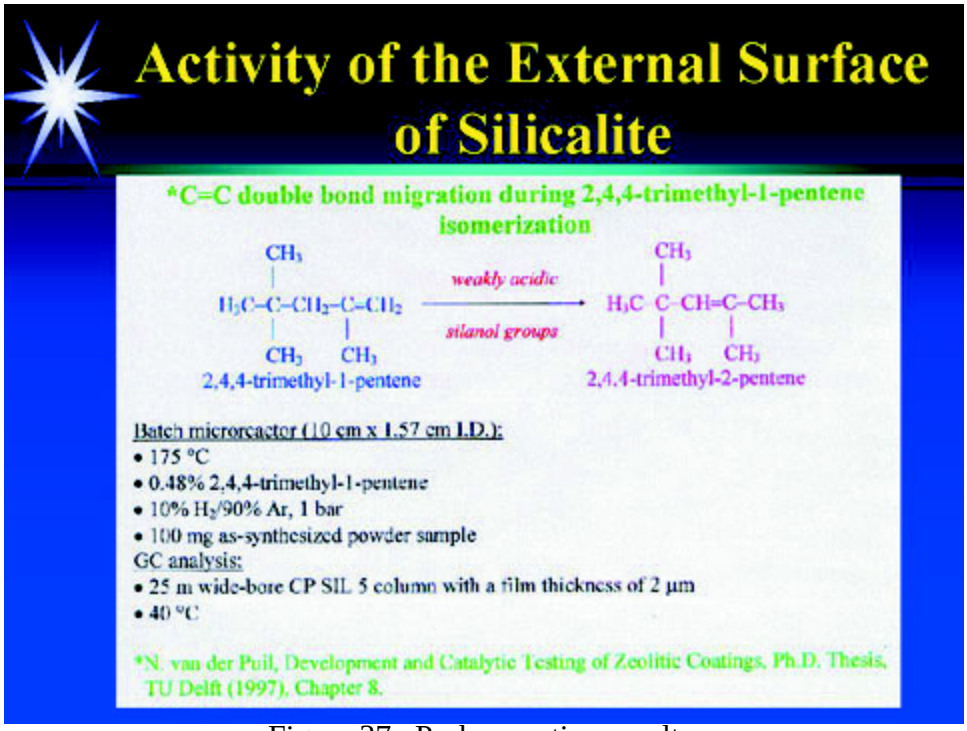


Figure 37. Probe reaction results.

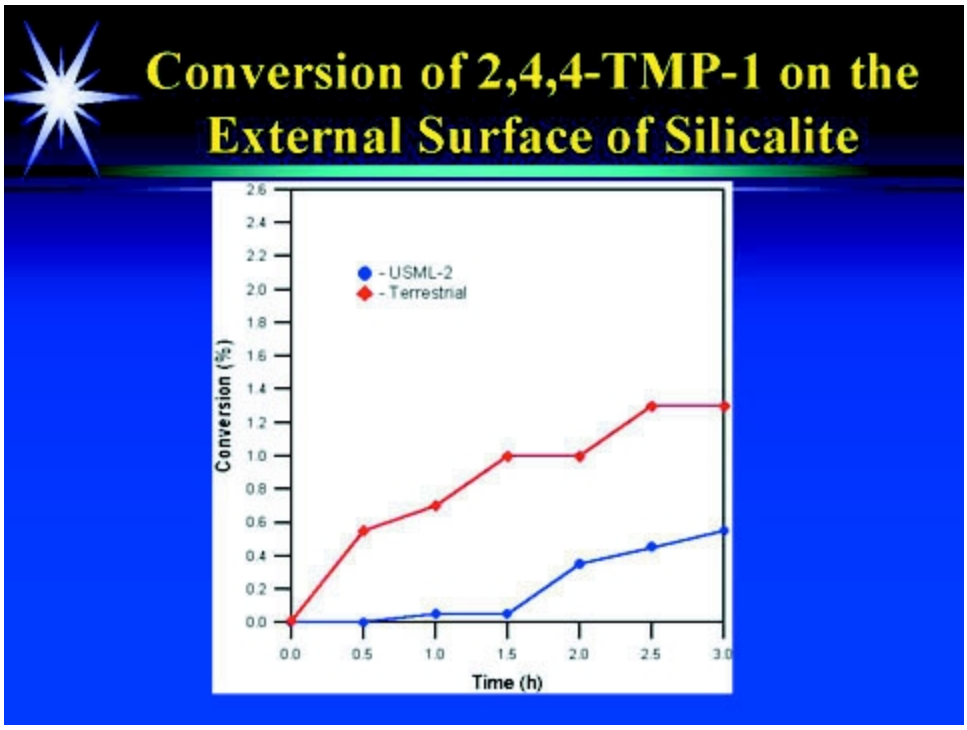


Figure 38. Zeolite X external surface comparisons.

Zeolite beta is a more complicated zeolite material (Figure 39). The size is about the same. One of the problems with this is to make it so it has a very nice, uniform crystal structure. This is what we get

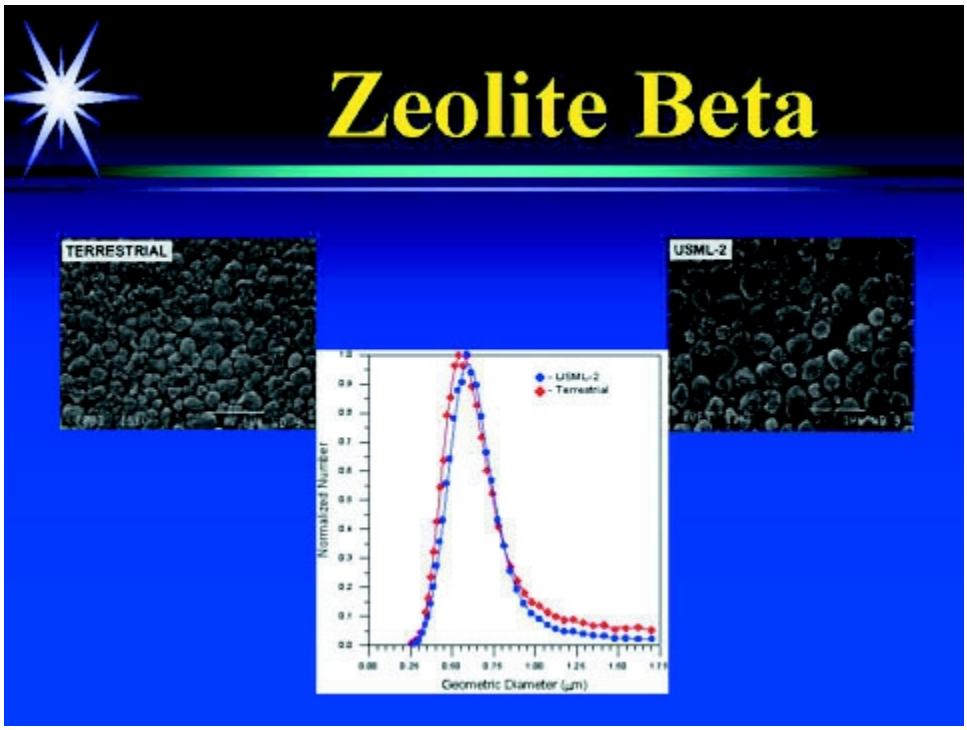


Figure 39. Zeolite beta.

typically, terrestrial crystals, and this is what we got from USML-2 (Figure 40). Consistent with most of the space crystal work I've seen, we have only a line and point defect. Other than that we don't have any

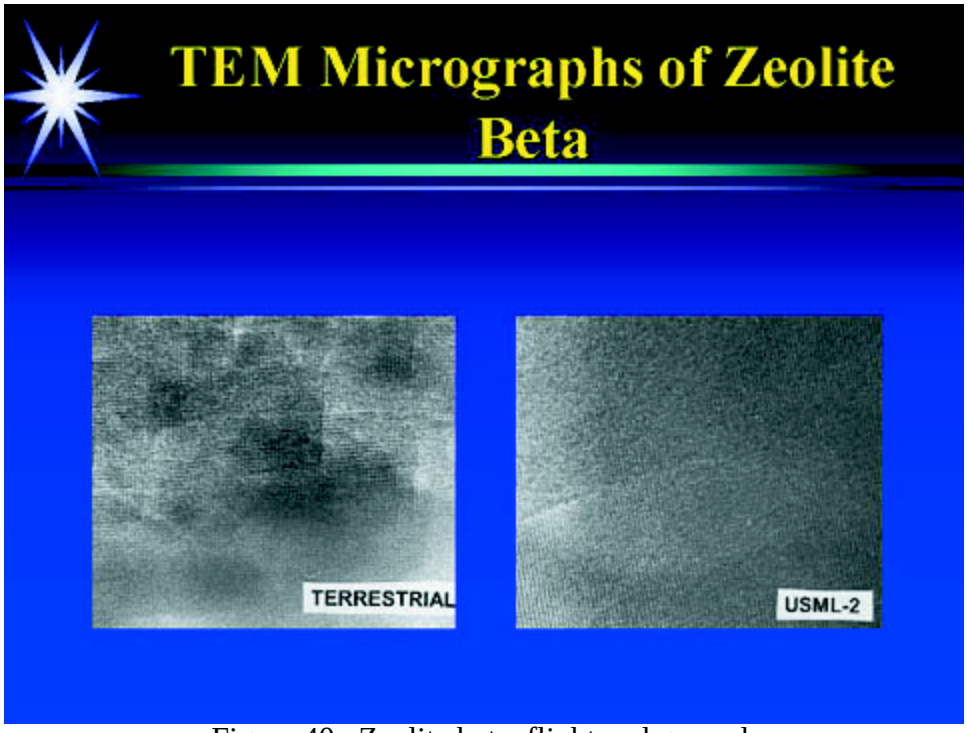


Figure 40. Zeolite beta, flight and ground.

defects in that crystal. This is the only zeolite beta crystal with this degree of perfection that I'm aware of. Looking at the external surface of beta, which is now being used as a replacement, as a catalytic cracker to produce gasoline, we begin to look at a different set of reactions specific to it (Figure 41). The first thing we found is the outside surface, in terms of its Bronsted acidity, was pretty much the same. There was no

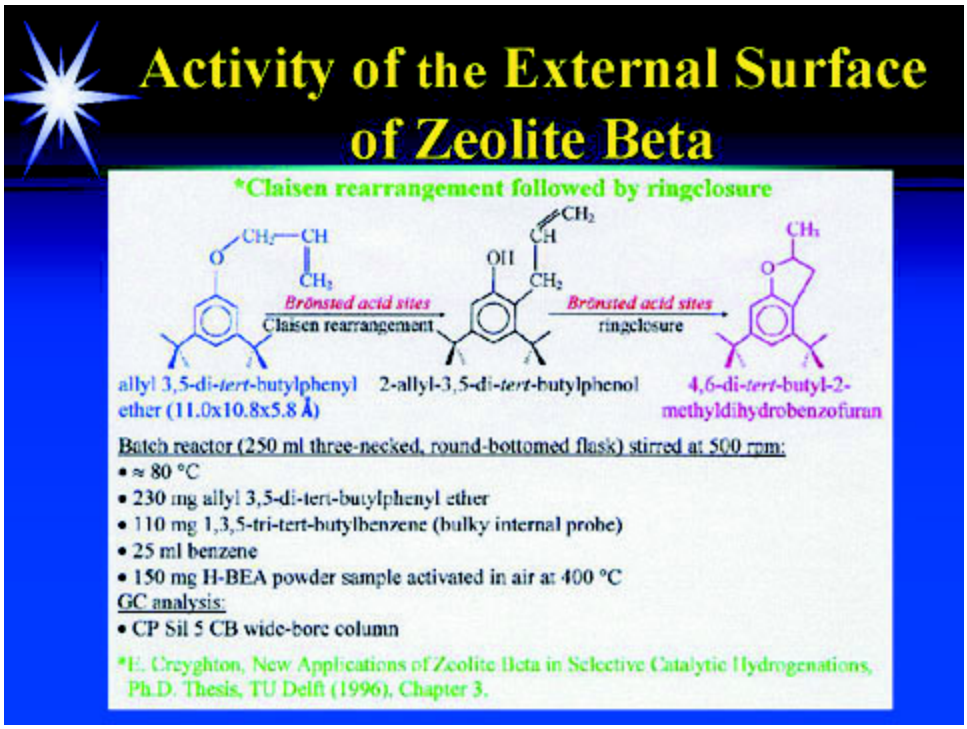


Figure 41. Zeolite beta, external surface.

significant difference between the two (Figure 42). When we looked inside, we get a smaller molecule for conversion, the micropores, where most of the conversion is done. We begin to look at the Lewis acidity (Figure 43).

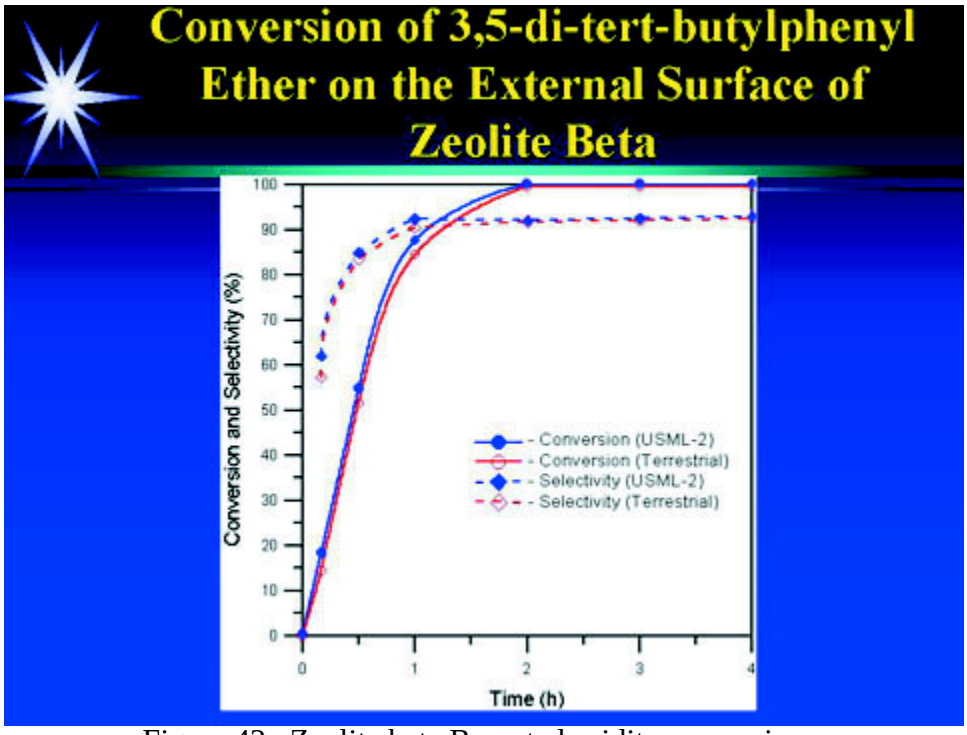


Figure 42. Zeolite beta Bronsted acidity comparison.

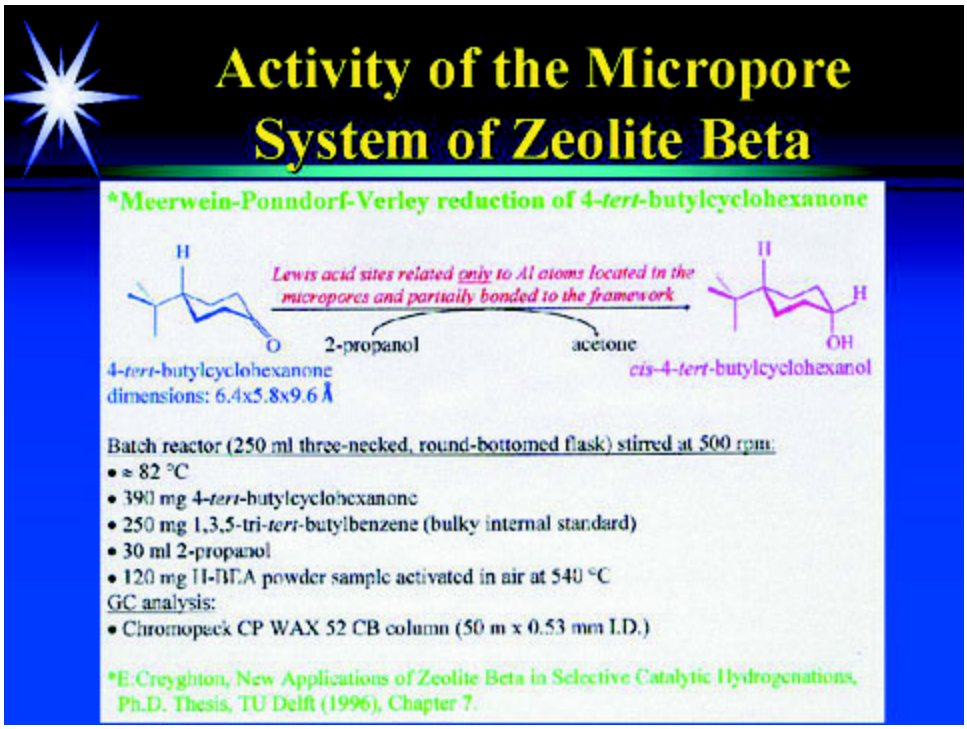


Figure 43. Zeolite beta Lewis acidity.

We did this work in conjunction with Van Beckham's group at Delft University. They are among the best reaction research engineers worldwide in this area. We had a lot of collaborations with the Europeans. What we found is a significant difference in the conversion for a given selectivity (Figure 44). That means the reaction is occurring on the same site, and we are producing the product we want. There is no confusion

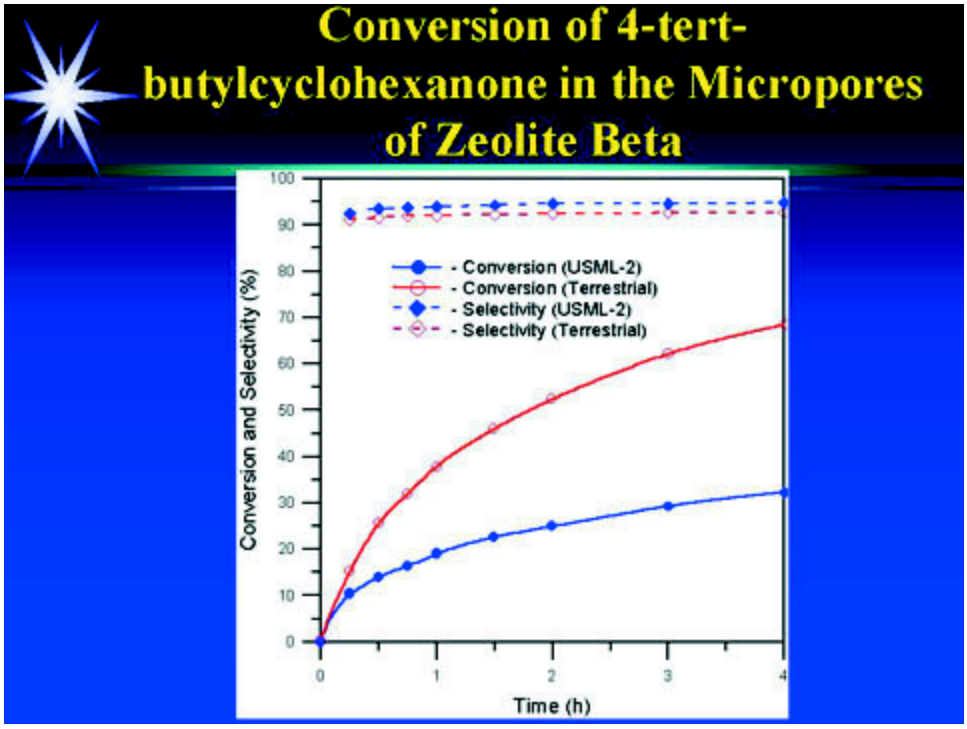


Figure 44. Zeolite beta conversions for selectivity.

about, well, is this on this site or another kind of defect site. It's on the right site, but we can affect the degree of conversion. That means that we can control the rate of reaction to a specific product and the selectivity to that product within some pretty broad ranges. That has a lot of potential impact, and it's why we now presently have about 1.5 to 1.6 dollars from external sources for every dollar that NASA puts into the program. That is coming primarily from the chemical process industry. That's because of these results. So we conclude a couple of things (Figure 45). The first thing I concluded from this is that I should fly every flight. But in lieu of that, we were able to prove that you can form large uniform zeolites for structural determination, but we went far beyond that. We were really interested in defect engineering. We never talked a lot about it, because it's a very difficult thing to do, and we fell into it more than engineered it. In any case, we were able to adjust the silicon-aluminum ratio, the degree of perfection, and everything so far indicates that we can adjust the Lewis acidity for sure and probably the Bronsted acidity within some broad ranges. We're not going to make catalysts in orbit. Everybody needs to understand that. But if we can learn how to control the fluid dynamics to do it on the ground, that's really where the payoff is.

So in my opinion, this research leads to the International Space Station (Figure 46). I believe our future will build on our past, and that we should all learn from the lessons we've heard in the last few days of how to do things efficiently, quickly, because again, at least in the commercial business, time is money. Thanks for the time.

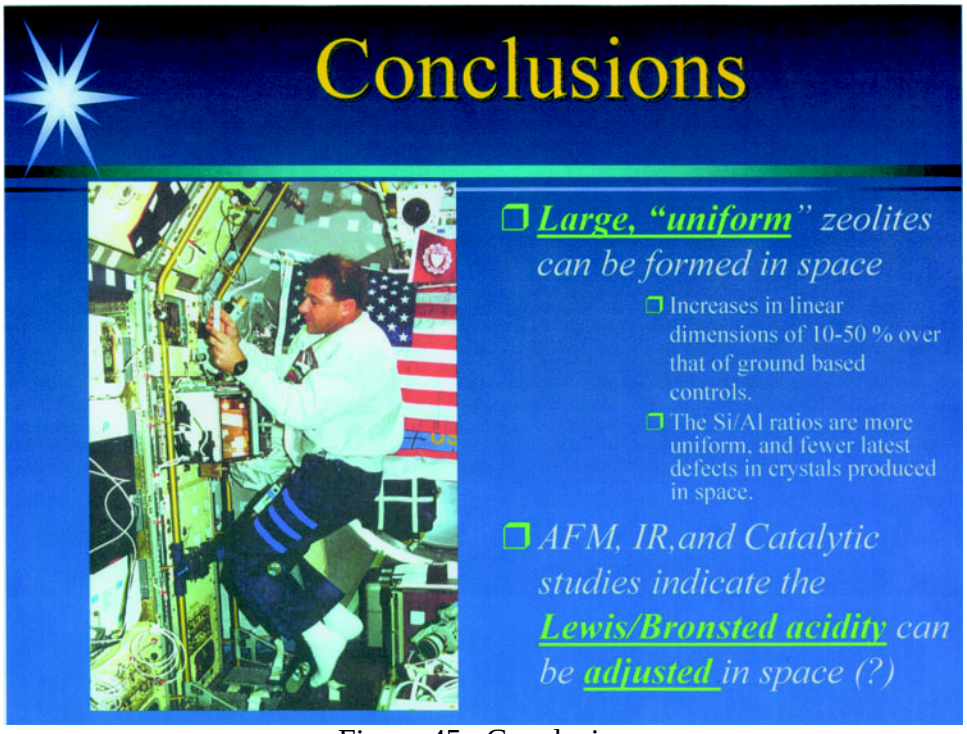


Figure 45. Conclusions.

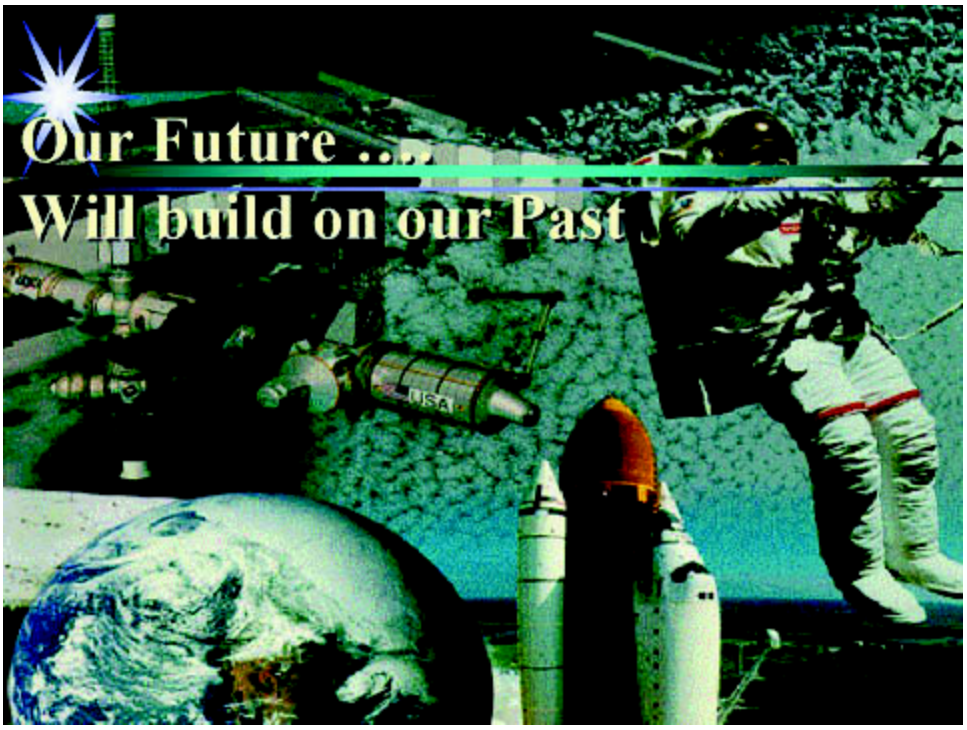


Figure 46. Future research.

Microgravity Science Research Panel
Dr. Bradley M. Carpenter, Panel Moderator

It is very difficult to pick representatives for this forum because there are so many people who have made important contributions over the history of the Spacelab program that you are certain to leave out important people in any reduction to five representatives. I would like to make that excuse my apology to individuals who haven't been able to tell their story here today. We have asked some of the legends of microgravity to talk about not only their research, but about some of the contributions that they feel have been important to the field during their time with the program.

Dr. Eugene Trinh received his Ph.D. in applied physics at Yale and didn't waste too much time arriving at the Jet Propulsion Laboratory where he worked with Dr. Taylor Wang. Taylor goes back to the late 1970s and early 1980s in containerless processing and at the time of the USML (United States Microgravity Laboratory)-1 flight was a professor at Vanderbilt University. Gene was a payload specialist on the USML-1 mission, continues as a principal investigator in the microgravity program and is distinguished with his diversity. He has researched in three different disciplines in microgravity; he's the only PI I know who has that kind of breadth. He works in materials science, fluid physics, and in biotechnology. He's certainly a Renaissance figure in the microgravity program.

Dr. Lawrence DeLucas, together with Dr. Charles Bugg now the CEO of BioCryst, was in at the creation of our protein crystal grown program. Larry heads the Center for Macromolecular Crystallography at the University of Alabama at Birmingham and has served as the senior scientist for Space Station, bringing his energy and dynamism to that function as well as the work that he continues to do for the University of Alabama at Birmingham. He is a Principal Investigator (PI) in the microgravity research program as well as in the space products program. He has an unusual range of interests in the microgravity program, and he's here to talk about some of what he has done.

Dr. David Larson is someone who is truly well equipped to give a perspective in two directions. He is a materials science PI who goes back to the Apollo/Soyuz test project and Skylab, and then forward as the current chair of the Space Station Utilization Advisory Subcommittee. Dave is probably as knowledgeable as any PI in the country on the capabilities and potential of the Space Station. He is currently a professor of materials science at the State University of New York at Stony Brook. Previously he worked for about 26 years at Grumman when it was an airframe manufacturer. He continues in our program now with research in alloy solidification.

The isothermal dendritic growth experiment (IDGE) is something that we have particular pride in within the Microgravity Research Program. It represents a confluence of interests between the physics community which had been attracted to dendritic growth as a paradigm for pattern formation in physical systems, and the more practical side of materials science where the investigators are interested in understanding dendritic growth as a general phenomenon because of its influence in materials properties. The person who

has done the hands-on work for IDGE for a number of years is Dr. Matthew Koss. The principal investigator is, of course, Dr. Martin Glicksman, who has been working in dendritic growth since the early 1970s. Matt has been working on this since 1990 and, as I think Marty would admit, has most of the day-to-day responsibilities for making isothermal dendritic growth a success right now. He will tell us about the three flights that IDGE has had in our United States Microgravity Payload (USMP) program over the 1990s.

Our last speaker, Dr. Simon Ostrach, is one of the really great figures in contemporary engineering research in the United States. He goes back a long way. You wouldn't know it to look at him, but he was a student at George Carrier, graduated in the late 1940s, went to work for NACA (the predecessor of NASA) and rose to the level of branch chief at Lewis before moving on to a long career in academic research at Case Western where for many years he was the Wilbert J. Austin Professor of Mechanical Engineering. A few years ago he loaded up his Corvette, drove across campus and took up a new job as the director of the National Center for Microgravity Research on Fluids and Combustion. Si was the PI for several microgravity experiments in the 1990s in Spacelab, for the surface tension convection experiments on USML-1 and USML-2. This is only part of his career in authoritative contributions in thermally driven flows for which he has been widely recognized, including his membership in the National Academy of Engineering where he currently serves as the Home Secretary. Those are a few of the highlights of his career, and he's here to tell you about his research.

I would like to thank all of our speakers.

Thank you very much for your introduction Dr. Carpenter. I very much appreciate your generous characterization as a "Renaissance Man." It sounds a lot better than "Legend."

I came right out of graduate school as a postdoctoral fellow at the Jet Propulsion Laboratory (JPL). I had done my thesis work on acoustic levitation applications to the properties of superheated and supercooled liquids. I thought that was kind of esoteric and a little bit out of the ordinary, but little did I know that I was going to stray even further from the beaten path.

It took me about four years to come from primarily laboratory research, into a full-fledged flight program. Taylor Wang and I were selected as payload specialists, myself as alternate payload specialist (a very good name for backup), for Spacelab-3. Spacelab-3 was the second Spacelab flight and actually took place before Spacelab-2 (another thing that I had to remember). I thus came directly from research into the flight program, and this unbroken chain of events pretty much led me to a complete and total immersion into the microgravity flight experiment program and into the Spacelab era.

However, before I go on to describe the science, I would like to say that I regret that the Spacelab era is over. It has given me the unique opportunity to participate in one of the most exciting scientific adventures of recent times. I am really grateful to have been able to do that, and to have met so many dedicated scientists and engineers both at NASA in the United States, in academia, in Europe and in Japan. I hope that I will be able to keep the same working relationship as we transition to the Space Station era.

Today I would like to address some of what we accomplished in microgravity and what is of some value to maybe yourself and to everybody. I would like to answer three basic questions, and I will start with the synopsis figure (Figure 1).



Figure 1. Synopsis of Containerless Experimentation.

The first point is: What have we contributed? The answer is pretty simple. We have answered some questions on some basic problems, and we have provided some solutions. The bottom line is: we have contributed to the advancement of fundamental scientific understanding.

The second point I would like to make is that the scientific program and the experiments in space have jump started the introduction of containerless technology. This is a brand new experimentation approach usable both on the ground and in microgravity. So not only advancement in science has been achieved, and answers have been obtained, but a concrete contribution to technology applicable to both Earth-based as well as low gravity enterprises has been made.

The last item I would like to talk about is the fact that the Spacelab phase has really provided a necessary transition to the Space Station era. More specifically, I am addressing the scientist's interface with his experiment. Doing your experiments in a laboratory is nowhere near like doing an experiment on Spacelab. Whenever I investigate something for the first time, I myself never quite trust the results if they come out positive, or as I expected it. It is definitely an iterative process. By doing Spacelab experiments, we have been able to implement this iteration in our procedure through the use of dedicated payload flight crew. This type of facility and capability has taught us how to perform on-orbit science, and has acclimated us to work on other types of experiments on the Space Station. Because of this experience, we will be better prepared for reduced crew involvement, and we will be able to learn how to develop effective and productive tele-operations, for example, and to continue to interface with our experiments on a close basis.

Since I've been doing mostly containerless experiments, I will limit myself to that topic today. I hope to provide some specific examples that hopefully will illustrate the three points I have just outlined. I will describe mostly containerless experiments in fluid dynamics and I will explain a little bit later what containerless experiments are.

Fluid dynamics and containerless processing experimentation technique really look at three-dimensional free surfaces without interference from any container. We can do that type of thing on the ground with clever levitation techniques; but you will see that there is some inconvenience that we have to put up with when we deal with one G experiments. These inconveniences and major drawbacks are virtually eliminated when we go to low gravity.

In the containerless experimentation context, we are looking at the dynamics of the free surfaces for various reasons: To understand the physical and chemical phenomena affecting these surfaces, to model the dynamics of other relevant natural systems, or to measure the properties of materials under specific restricted conditions (Figure 2). Also, we can look at low temperature three-dimensional surfaces or very high temperature three-dimensional surfaces. For example, a drop of molten steel freely suspended in a vacuum or in a gas is a three-dimensional surface which, because of surface tension, has a spherical shape. The spherical shape is probably not that important experimentally, but it is crucial for theoretical developments because it allows various approximations tied to the axial symmetry. By developing the appropriate techniques, we can study this high temperature liquid material under high purity conditions, and in a thermodynamic state that is not accessible without the free suspension. It is clear that microgravity conditions are ideal for this type of investigation.



Figure 2. Introduction to fluid dynamics.

What can we do to handle drops and bubbles in one G and in low gravity? We basically levitate them and we can do that in various ways. This example is mentioning a couple of approaches using ultrasonic and ultrasonic-electrostatic hybrid type technology (Figure 3). In this instance, we show a Glovebox flight apparatus that we have flown before. The figure shows an ultrasonic generator that provides a standing wave. A liquid drop can be positioned in space and levitated on the ground fairly easily. The acoustic wave, in this case the field, provides the levitation and the deforming force, and also the rotation of the drop capabilities. So it's not enough just to look at the sample; you have to interface with it, interact with it, so

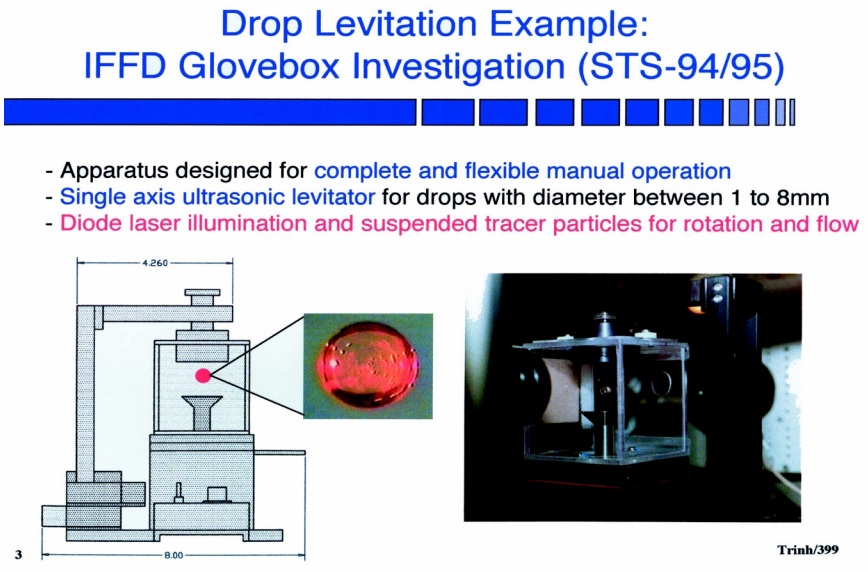


Figure 3. Drop levitation example STS 94/95.

that you can measure its response. By measuring its response you can determine its physical and chemical characteristics.

The other type of experiments you can do on the ground, and that happens a lot more naturally in low gravity, of course, is to trap a gas bubble in a liquid (Figure 4). Free gas bubbles in liquids in microgravity are at this stage somewhat of a curse. The problem is how to get rid of them in places that you don't want them. For example, in heat transfer surfaces used in boiling heat transfer, gravity provides you the removal capability of those bubbles from a heater surface, and therefore enhances the heat transfer characteristics of a boiling heat transfer process. In low gravity, one no longer has that natural removal ability. You have to actively remove those bubbles. There are some current investigations actively looking at ways to implement bubble management in low gravity. These projects are related to what is going on in microgravity and ultimately will enhance the capabilities for the human exploration and development of space because the management of fluids is a fundamental technical requirement for developing low-gravity life support systems.

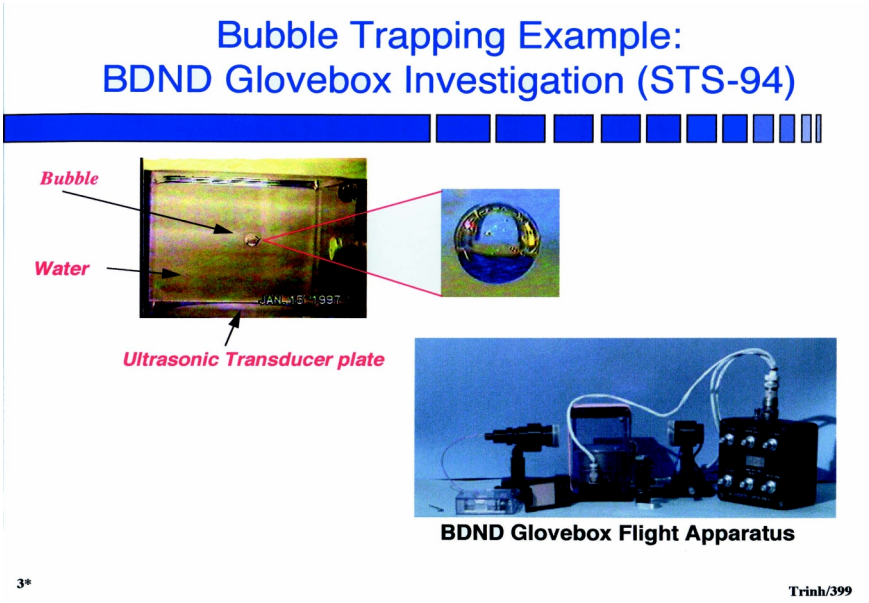


Figure 4. Bubble trapping example STS 94.

In this second example you have a liquid filled cavity, and cleverly introduce an ultrasonic sound field to manipulate the fluid particles around. The bubble or the drop, if it's an immiscible drop in the liquid, can be trapped and manipulated with sufficiently well designed standing waves, and one can visualize how appropriate engineering development of this basic physical phenomenon could lead to an effective bubble management approach.

In addition to controlling its motion and location, what can you do when you have a drop that is sitting there instead of flying around and falling from gravity? For example, you can look at the internal flow (Figure 5). You can understand how each drop behaves and what would happen, for example, if you processed the drops in low gravity and imposed some specific perturbation. In Figure 4 we can see examples of standard fluid dynamic flow involving single droplets. In this case it shows the trajectories of tracer particles inserted into a vibrating drop. You can resolve some vibrational motion and also some steady circulatory motion. What practical application can one make of these model systems? One example would be to carry

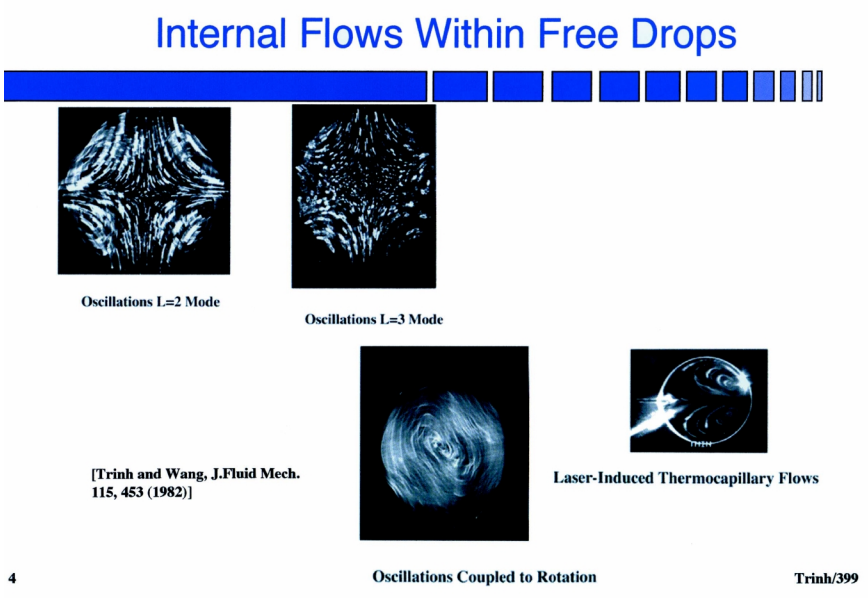


Figure 5. Internal flows within free drops.

out a detailed study of the effects of time-varying motion on steady convection. By controlling the vibrational environment of a free drop and monitoring the internal flows, one can understand the coupling between time-varying motion and convective flow. This is of particular interest to space-based platforms that are subjected to a wide spectrum of oscillatory perturbations. One needs to assess the effects of these vibrations on the microgravity environment, in particular, what would affect the lack of convective motion.

In a two phase flow system, basically a system where you have a multitude of bubbles immersed in a liquid, you can drive these bubbles into motion and actually induce motion in the outside flow. Under certain circumstances, and because gravity and gravitational effects due to buoyancy have been eliminated in low gravity, you want to actively replace those capabilities by artificially driving those bubbles or drops into motion in order to stir up the stagnant liquids to enhance heat and mass transfer (Figure 6). This figure

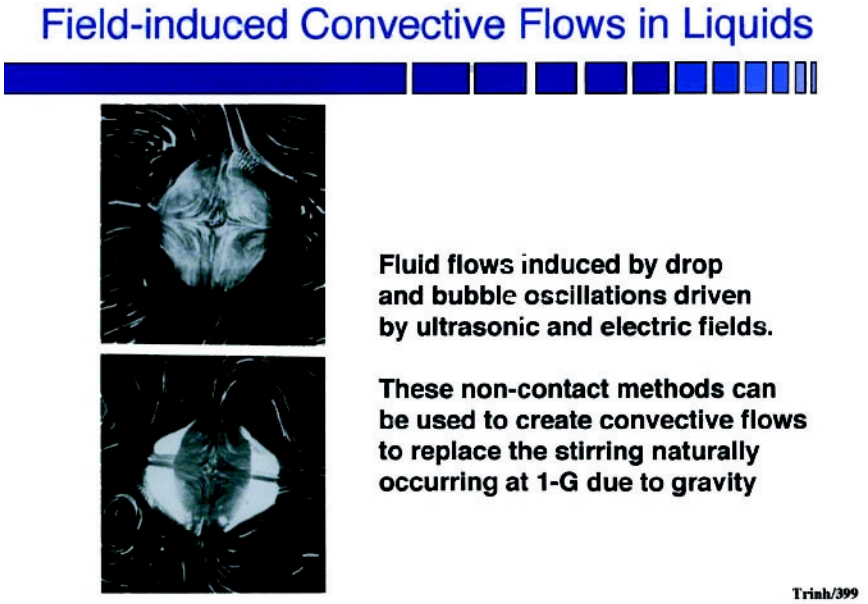


Figure 6. Field-induced convective flows in liquids.

shows that if one drives these fluid particles into motion in a non-contact manner by using electric or ultrasonic fields, one can achieve a reasonable degree of convective motion that would mimic gravitationally-induced motion.

Going up in temperature in order to carry out the same type of droplets experiments is a viable proposition, except it's a little bit harder. Electromagnetic levitation had been valid a while ago, in the 1920s, and people have actually levitated conducting materials and heated them in a vacuum and in inert gases for a very long time (Figure 7). They have been mainly looking at the metallurgical implications of processing in a containerless fashion.

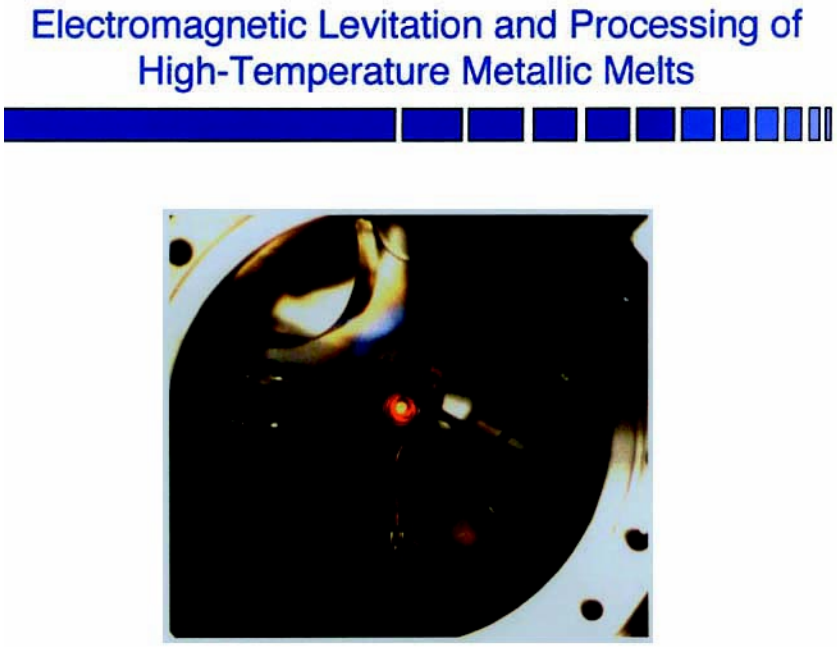


Figure 7. Electromagnetic levitation and processing of high temperature metallic melts.

I would like to digress a couple of seconds here to mention that the Spacelab era has also allowed the contribution from the German Space Agency in the form of a flight facility called TEMPUS used on the IML-2 and MSL-1 flights. This is a flight electromagnetic levitation facility that has allowed the investigation of high temperature melts. Not only has it been successful, and produced a lot of useful data, but also it's leading to the Space Station era with the next generation flight experiment hardware to continue this type of containerless processing work.

At a meeting of the Minerals, Metals, and Materials Society in San Diego, Dr. Michael Wargo gathered a workshop together to actively plan for the next phase of containerless experimentation on the Space Station. This involves active participation by both the European and the Japanese space agencies together with NASA.

Why do we want to do experimentation in a containerless fashion in microgravity? We have some definite practical Earth-based applications that could be dramatically improved if the effects of gravity were mitigated. For example, there is a keen interest in knowing the properties of metallic and other materials at very high temperature for specific applications in manufacturing. The containerless approach is ideally suited for such measurements because of the avoidance of impurities and the lack of requirement for prac-

tical high temperature container materials. Also of great interest are the properties of these materials in the molten supercooled state that can be reached using a containerless approach. Today, a combination of these needs and the availability of new non-contact measurement capabilities developed by NASA provides the motivation for implementation of these measurements in a low-gravity environment. The problem on the ground, as I mentioned before, is that the fields that are used to levitate the samples actually interfere with the motion; they deform them; they rotate them; they drive vigorous internal circulation; and they basically play havoc with them. The idea of going to low gravity is that you can reduce the intensity of these fields and therefore get rid of these obnoxious effects, perform some investigations not possible on Earth, and carry out more accurate scientific measurements.

The full potential is achieved in microgravity. Not only can you look at materials processing and also characterization of materials, but you can also do active experiments in fluid dynamics and look at some scientific problems that have been raised in the scientific community for a long time. For example, a new flight experiment that has recently been approved at NASA looks at the dynamics of wave turbulence on the free drop in space. This is going to be a potential Space Station experiment.

The addition of a novel capability and technology actually allows you to look at your problem in a different way. This may be a change of mind-set, a shift in paradigm, or looking outside the usual box (Figure 8). The microgravity containerless experiment facilities flown on the Space Shuttle and Spacelab have been divided into drop dynamics and high temperature facilities, including the TEMPUS I previously mentioned. We can use larger drops at low gravity because the surface tension pretty much takes over. Larger drops allow a slowing down of the dynamic processes to allow improved experimental time resolution. One can also drastically reduce the field intensity required for levitation. The levitation field-induced effects, therefore, become more acceptable.

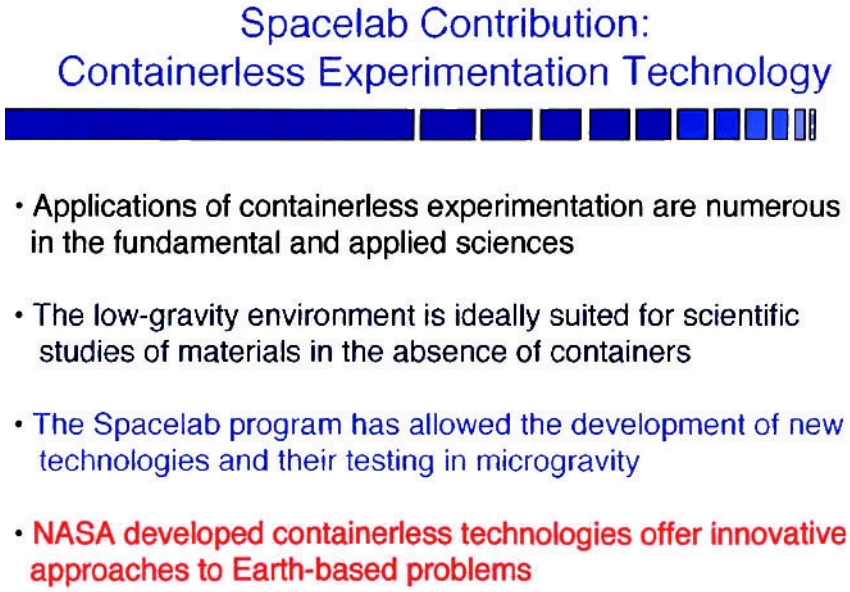


Figure 8. Spacelab contribution to containerless experimentation technology.

Spacelab missions we have flown with the Drop Physics Module were on STS-50 and STS-73 (USML-1 and USML-2). The TEMPUS, the German provided flight facility, has flown on STS-65, IML-2, and STS-

94, MSL-1. These are pictures of the Drop Physics Module with Kathy Thornton and Ken Bowersox. This was taken during the USML-2 mission (Figure 9).

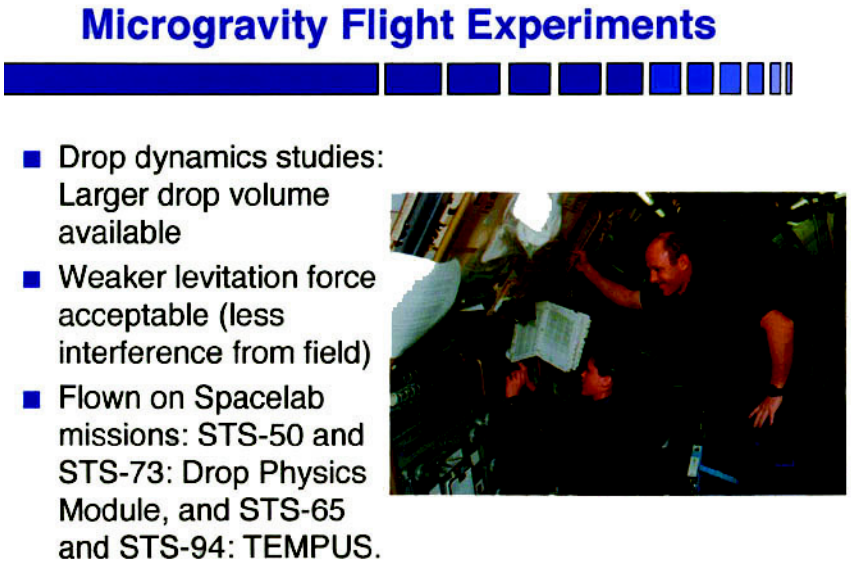


Figure 9. Microgravity flight experiments.

The drop physics module was used to position and to manipulate drops in low gravity. We were trying to look at the dynamics of oscillatory and rotational motion, and therefore to also look at the properties of the free surface and surfactant-related effects. This facility was totally crew-operated, and required constant cognitive and creative human input. By exercising this capability provided by the availability of a dedicated payload crew, we have acquired a considerable database of information directly relevant to the operation of such a facility in microgravity and to the behavior of free drops within a restoring force field. This information is required to design future instruments that can be automatically operated, or at least remotely controlled via tele-operation.

These figures are taken from the USML-1 mission (Figure 10). You can see that you have rotationally-induced fission. Various drop configurations relate to the dynamics of shape oscillation. Also shown is a stage of the coalescence process with a very low viscosity liquid. This low viscosity allows an oscillatory behavior after the coalescence event that is inhibited at higher viscosity.

To do equal justice, I have another slide from the USML-2 mission showing coalescence stages for high viscosity liquid (Figure 11). You can see the dynamics. There is a little bit of a difference in terms of the shape during coalescence. I believe that the major contribution of the Spacelab scientific investigations into drop dynamics is that they have provided experimental data on specific problems that are now considered beyond the capabilities of current theoretical tools.

To clarify my contention that we have provided answers to some theoretical questions, let's consider a very simple but old fundamental problem. Some time in the last century there was a Belgian scientist named Plateau. He was blind, but fortunately had a reliable assistant. He was conducting experiments looking at the rotational shape of drops. These are drops that are rotating along a fixed vertical axis on Earth but in gyrostatic equilibrium. That means that the shape is at equilibrium and the rotation in the fluid is uniform; i.e., there is no differential flow. He was looking at what kind of shapes you could get. Of course he was

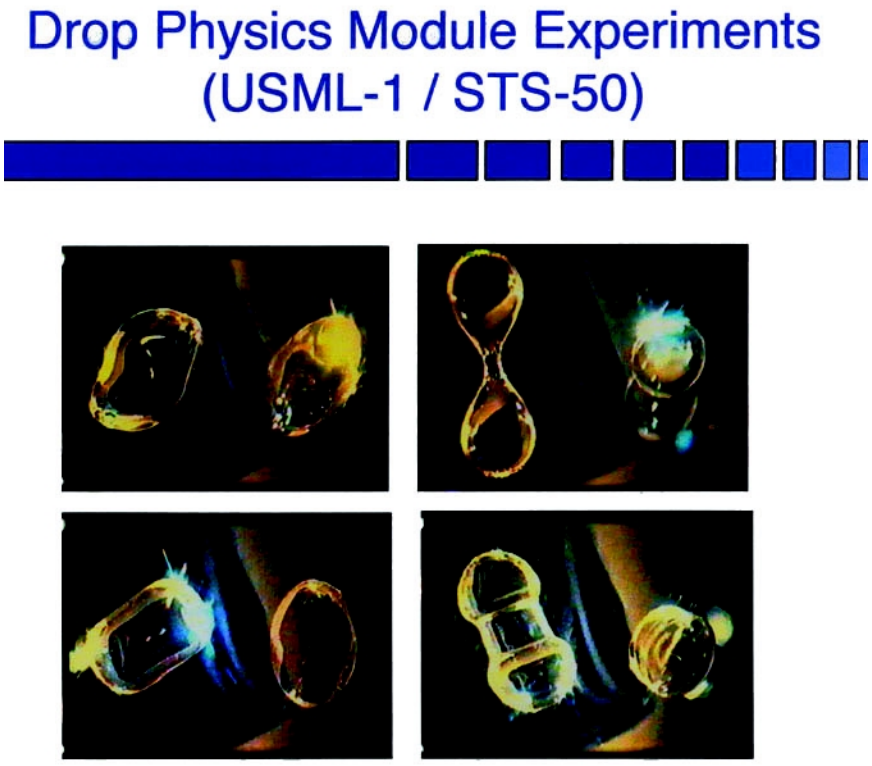


Figure 10. Drop physics module experiments, USML-1.

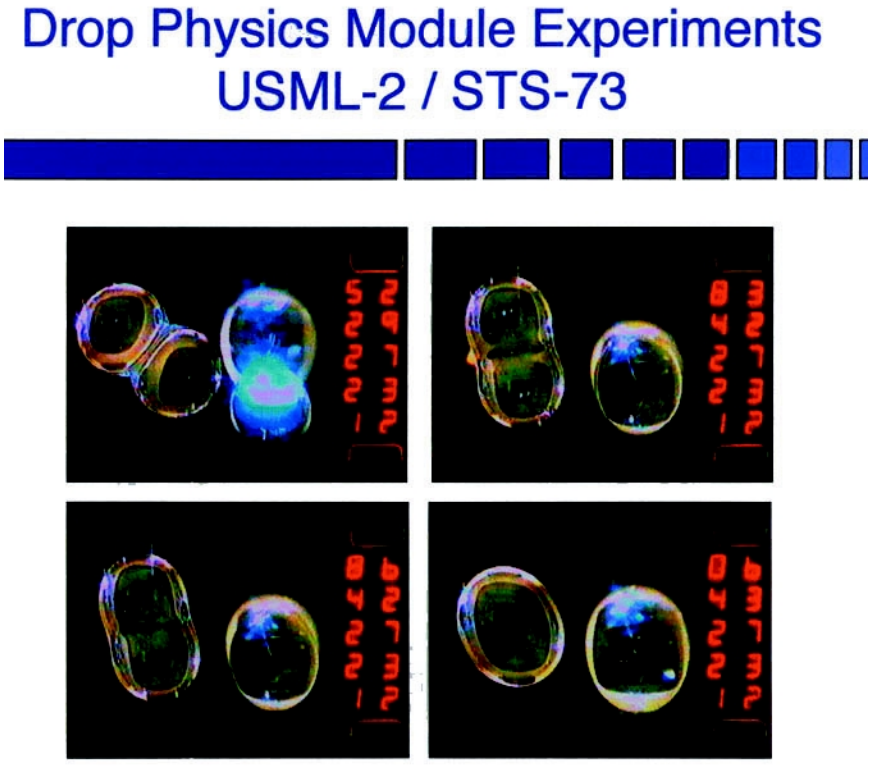


Figure 11. Coalescence stages for high viscosity liquids.

not a member of the Spacelab flight experiment team, and only had a ground-based apparatus, a neutral buoyancy tank consisting of a host liquid, and inside it, another drop held by a rod and a plate. He was just spinning them manually, and he was looking at the different shapes taken by the drop as he rotated it faster and faster.

The idealized problem is this: let's say that you trap a free drop. It's pretty spherical. You hold it over there without touching it, and you can start spinning it. You can see it from the top and the side. You start spinning it a little faster and the drop will flatten out and become oblate. If you look from the top, it will still have a circular cross-section. The question is what other shape will it assume as you spin it faster and faster? Plateau could obviously not do the idealized problem because he needed a host fluid, and he was driving the drop by a rod and plate. The shapes achieved by rotating in such a fashion were not in gyrostatic equilibrium because of significant differential motion. He found that the drop would first remain circular when you looked from the top, then it took on a two-lobed shape, and ultimately it would assume a toroidal shape with no fluid in the middle (basically the shape of a donut).

In 1980, Bob Brown and Skip Scriven published a paper, a numerical analysis of the problem, but they were predicting that the axisymmetric shape, which basically leads to the toroidal shape, would not exist because of intrinsic instability. But they also predicted a series of two-, three-, and four-lobed shapes as the rotation velocity was increased. The problem was to try to find out whether or not that was true.

Professor Taylor Wang at Vanderbilt University proposed an experiment and carried it out on Spacelab 3, USML-1, and USML-2. USML-1 provided the answer; and USML-2 confirmed that answer.

Plotted on the Y axis is a measure of the shape of the drop, the ratio of the longest dimension of the drop cross-section over the rest of the drop diameter when it is spherical (Figure 12). For example, if it's spherical, the ratio should be one. The dimensionless rotation velocity is plotted on the X axis. So it is looking like this, the elongation in the equatorial direction, and the rotation rate.

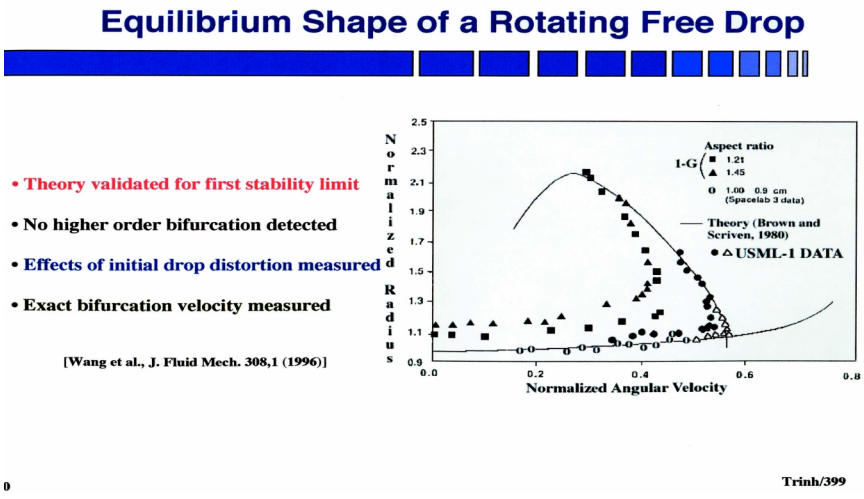


Figure 12. Equilibrium shape of rotating free drops.

The theory predicts that in mathematical terms specifically at this point you have bifurcation. Physically, at this point the axisymmetric shape disappears (becomes unstable). If you look from the top, it will no longer be circular, it will be two-lobed. In a nutshell, what we find out is that it's true if you conduct the

experiment in low gravity, and the Brown and Scriven prediction for the specific value of the bifurcation point velocity is accurate.

We can pretty much do that on the ground. Unfortunately, what you get on the ground are data sets like this, which basically are far removed from the theoretically predicted bifurcation limit. This bifurcation velocity has been non-dimensionalized by using the liquid surface tension, rest drop radius, and density. If you know what the density of the fluid is, and you measure the sample volume, you can calculate the surface tension. There is, therefore, also a practical aspect to knowing that, not just verifying the theory. You have a way to measure surface tension of, for example, a very viscous fluid like glass.

What has been found is that the theory is accurate in predicting the two-lobed bifurcation velocity, and that we cannot go beyond the two-lobed bifurcation to reach that toroidal shape, at least when you are in gyrostatic equilibrium. Also, if you carry out this experiment on Earth, distortion of the drop will vitiate the answer. This information is useful because most of the time you do experiments on the ground, and you want to measure these properties in your Earth-based laboratory. This result provides you a way to calibrate what you find on the ground, and to understand the effect of the distortion that you get with ground-based levitation.

One of the aspects of containerless manipulation involves driving free drops into oscillation. Basically you can introduce shape oscillation because surface tension acts like a spring for a drop that has been deformed by external fields (the equilibrium shape of a drop being spherical if you don't disturb it). Lots of science fiction movies now have very clever three-dimensional renderings of drops floating around in space, and the special effects people have done a tremendous job of simulating what happens to drops in low gravity, but I have to tell you it doesn't yet look quite right.

One can quantitatively measure the shape oscillation modes of a drop. These are resonance modes. Again, in the case of low-viscosity liquids, by measuring these resonant modes you can determine the drop surface tension, as well as the viscosity. In this case, the practical motivation for doing these drop dynamics studies is really to be able to measure properties of materials, and at the same time, to verify some basic theories on fundamental nonlinear drop dynamics. Access to low gravity allows you to verify the applicability of the linear theory of drop shape oscillations to the measurement of surface tension and viscosity. Levitated drops on Earth are generally distorted, and according to the experimental results shown in the figure (Figure 13), the distortion of a drop affects its shape oscillation resonance frequency, and would therefore influence the accuracy of surface tension measurement.

The surfactant industry is a multi-billion dollar industry and surfactants are used in food, cosmetics and pharmaceuticals. We cannot claim that we will solve the problem of a national deficit with this, but Professor Apfel at Yale University has looked at theoretical and experimental verification of some models for the action of surface tension.

In this case, if you measure the surface tension and the viscosity and the damping constant of a drop laden with surfactant, you can get some measure of the macroscopic characteristics of the surfactant. Surfactants drastically alter the surface dynamics of a drop or a free surface by using a very minute amount. So they don't alter all properties, but they alter the surface properties.

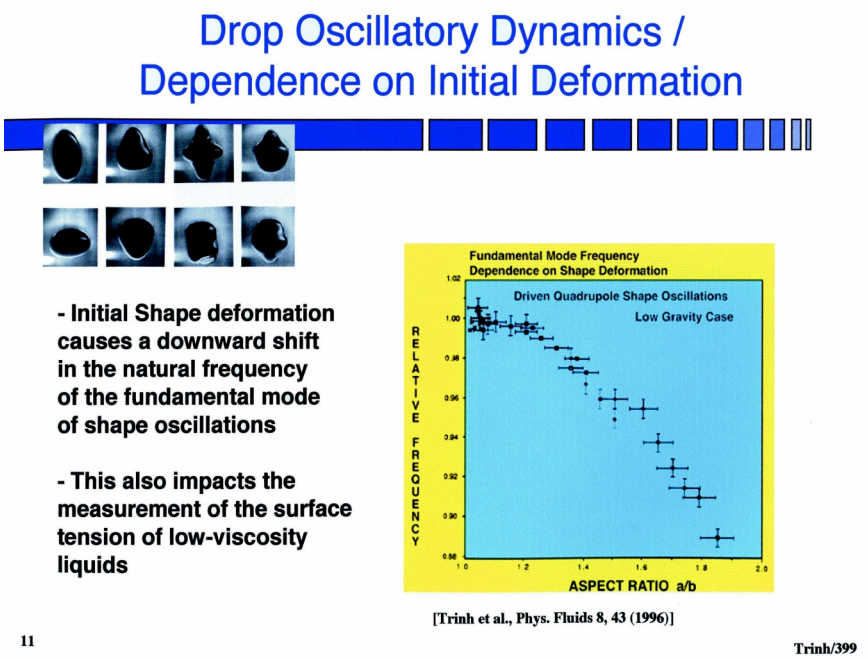


Figure 13. Drop oscillatory dynamics dependence on initial deformation.

Professor Apfel has been able to induce shape oscillation by squeezing a drop in space. It has not been possible to do this on the ground because of significant initial drop distortion at one G, and in low gravity you have a very quiescent drop that you can squeeze and release. He has achieved some very large distortions, and the response of the drop after the distortion release has been mathematically modeled. Not only has he achieved that experimentally, but he has built a theory to explain the dynamics of the drops, including the effects of surfactant (Figure 14).

There is a facility that has also been provided by the European Space Agency called the Glovebox. This is a great facility. We can design some very simple experiments for either getting some basic scientific results using a small apparatus, for checking technology or experimental hardware on orbit.

This is the Glovebox facility that flies in Spacelab. It also flies in the Shuttle middeck, and in Spacehab, and it has been redesigned to fly on the Space Station. The use of the Glovebox allows complete interaction between the experiment and crew member. This is really the ultimate utilization of this capability of having man-operated instrumentation and having the direct initiative and cognitive aspects of manned space flight. This viewgraph shows Glovebox experiments being operated by Mission Specialist Dr. Don Thomas and Payload Specialist Dr. Roger Crouch during the STS-94 (MSL-1) mission (Figure 15).

We have flown one of those very simple experiments. We can build it very cheaply; students actually design and build it. We looked at the effects of gravity on the response of bubbles trapped in an acoustic field. In a nutshell, the theory predicts that if you have a certain size bubble, the shape oscillations of the bubbles are predicted here. If you measure it on the ground, you get fairly good agreement for smaller bubbles, but as you go to larger and larger bubbles, because of the deformation and the effect of gravity you get answers that are fairly wrong.

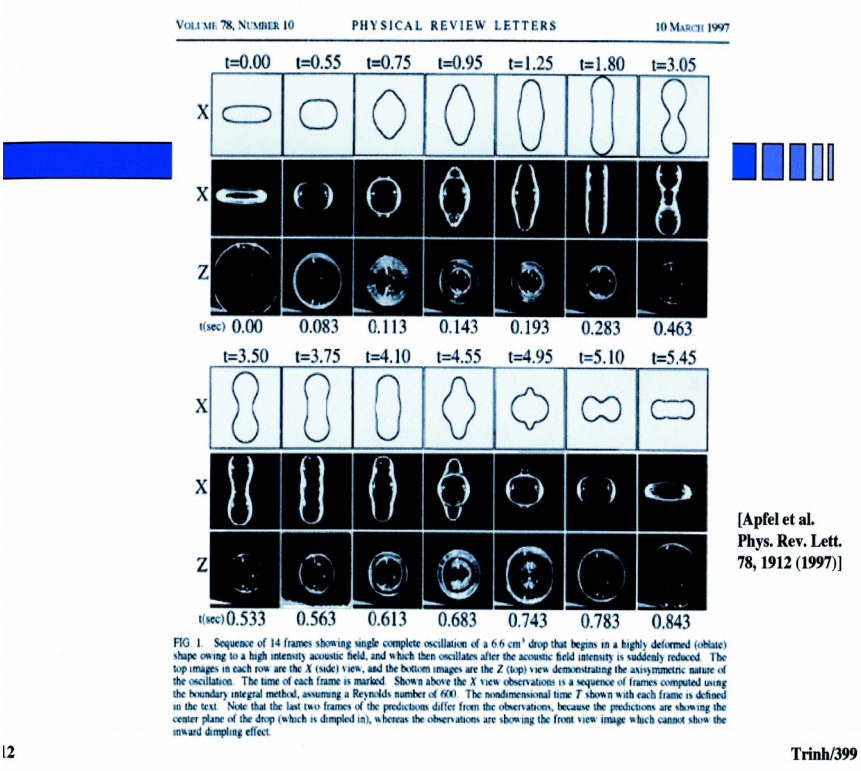


Figure 14. Effects of surfactants on drop dynamics.

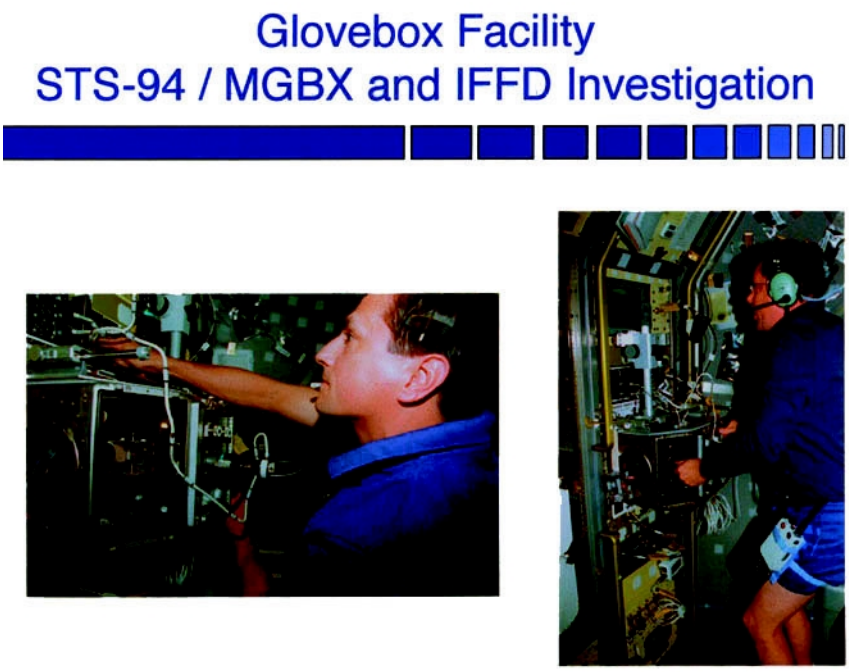


Figure 15. Operation of Glovebox experiments on STS-94.

Figure 16 summarizes some of the results. The graph shows the predicted and measured resonance frequencies of a single bubble immersed in water as the function of the bubble radius. The graph shows that

ground-based experiments produce results that deviate from the theoretical predictions for larger bubble radii. Low-gravity results indicate that this bias is removed when the bubble static shape distortion is drastically reduced (Figure 16). This is an example of a very quick Glovebox type experiment that provides some definite answers to some specific questions.

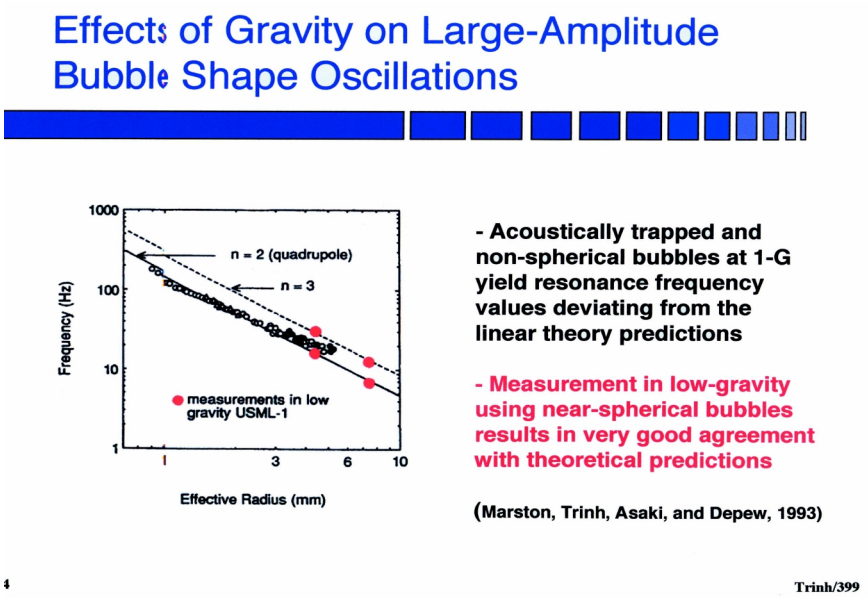


Figure 16. Effects of gravity on bubble shape oscillations.

Along with Spacelab flight instruments, we have been able to carry along the technology to develop more sophisticated high temperature devices. NASA has been responsible for introducing a brand new technology: the high temperature electrostatic sample levitation facility which was first developed at JPL. This allows you to levitate charged drops on the ground and heat them to very high temperatures and therefore investigate the properties of materials at very high temperatures, to use reactive materials, and to look at properties of very high temperature melts. A molten zirconium droplet is shown in Figure 17.

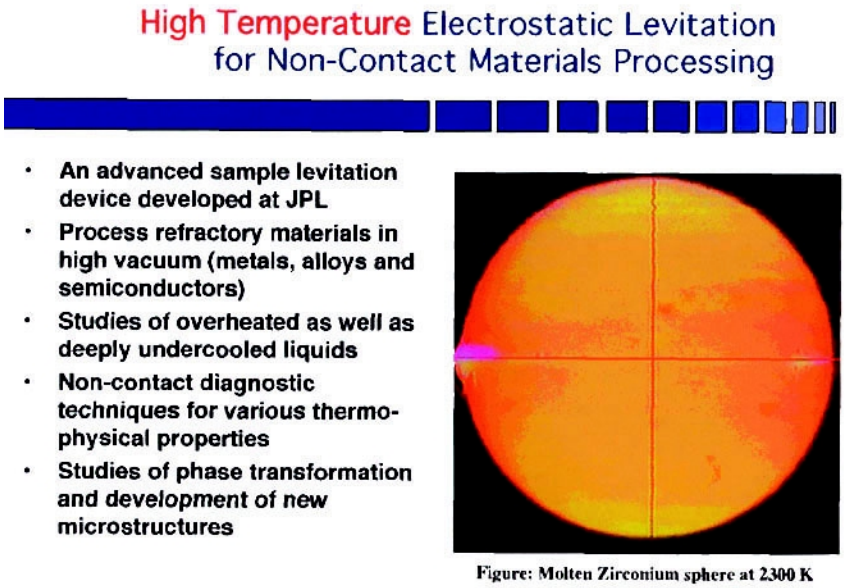


Figure 17. Molten zirconium droplet.

A variety of Earth-based and low-gravity experiments can be carried out with this facility, namely, investigations of the details of liquid-solid phase transformations, and measuring high temperature physical and chemical properties of high purity melts are now possible. For example, there is an interest in developing a new type of metallic alloy material obtained from the solidification of highly undercooled melts having compositions leading to a glassy structure. The use of this high temperature containerless experimentation facility will allow specific scientific experiments leading to an improved understanding of the fundamental physical processes governing this metallic glass formation. A schematic description of a JPL/Caltech apparatus is described in the last figure (Figure 18).

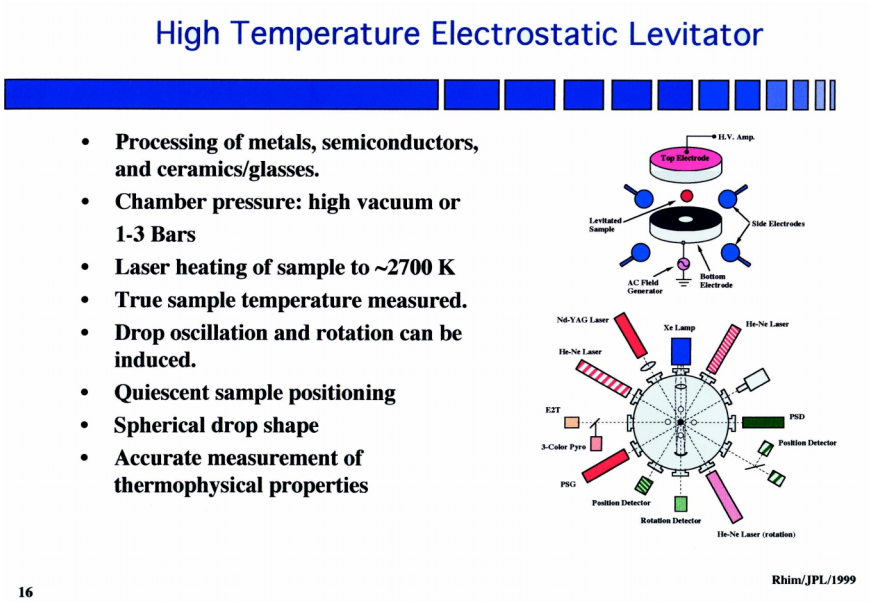


Figure 18. Schematic of a metallic glass apparatus.

The Japanese Space Agency has plans to introduce a flight experiment apparatus for the Space Station based on electrostatic positioning in microgravity.

Thank you very much.

I certainly want to echo what Gene Trinh said. It's really not fair for me to stand up here and represent the protein crystal growth community that NASA and other space agencies around the world have funded. Without this funding, today we would know absolutely nothing about why protein crystals grow on Earth or in space. When I first was approached by the director of our center, Dr. Charlie Bugg, about growing crystals in space, I laughed. I said, "Why in the world would anybody want to do that?"

Today the entire community is aware of what we are doing. They're not all aware of some of the wonderful results that have come from it and how it has impacted our ability to grow better crystals here on Earth. We are going to do a much better job in the future of making them aware of just what has happened because of this support from the various space agencies. If you look at the NIH goals, a major goal that they've had for the last five years, and it will continue and probably strengthen for the next ten, is structural biology and the human genome project. With all the different viruses and bacteria and various types of infective agents that we are now determining the complete genome sequence for, it's opening a world of about 200,000 new proteins that we need to understand the structure of. All biological systems work because of the three-dimensional structure of proteins that make up those biological systems. It's how those molecules interact, sometimes on their surface, sometimes within the protein in what we call the active site, that determines all biological functions and that is responsible for all disease processes. The impact of being able to grow crystals that are going to give us a higher resolution structure or perhaps let us determine the structure of a protein that we couldn't ordinarily have done is enormous today in biology and medicine.

With that, I want to say a little about how we got introduced to the field. When Charlie Bugg was invited to go to Marshall Space Flight Center, he sat in an auditorium like this and a scientist stood up — I wasn't there — and showed a picture of some inorganic crystals and showed how in space they had fewer defects and sometimes they were actually larger. Puzzled, he looked at this, but then they talked a little bit about why they think this happens. That convinced him, because protein crystals grow out of a solution, that it certainly was merited to try to do this. In addition, a German physicist named Walter Littke actually performed a microgravity protein crystal growth experiment. If you look at the experiment compared to the controls, there was a huge difference in what happened in microgravity versus on Earth.

That kind of data convinced us that we should investigate this. So working with people like Bob Naumann and Bob Snyder initially, I learned what Ostwald ripening was. I had never heard of that term before. Because of my training, I was lucky enough to train with people like Gene Trinh and Joe Prahl who taught me a little bit about fluid dynamics and what is happening because of gravity induced flows. I realized that it really made sense to try to eliminate these effects and see if in fact by doing that you can produce a better crystal. There have been so many people involved — Franz Rosenberger comes to mind today; Alex Chernov is really doing an awful lot to understand fundamentally what happens when a crystal grows, what parameters affect crystal growth on Earth. Then space is another parameter, just one of many parameters. So all these people have been developing data, coming out with important data, and Larry DeLucas is more applications minded. So I've been the leech. I look at what they discover, and then I figure a way we can do this to improve our yield of crystals, both on Earth and in space.

Along with being a leech, I have been funded by the Microgravity Division to also investigate some fundamental new processes that will improve the crystal growth process (Figure 1, Figure 2).

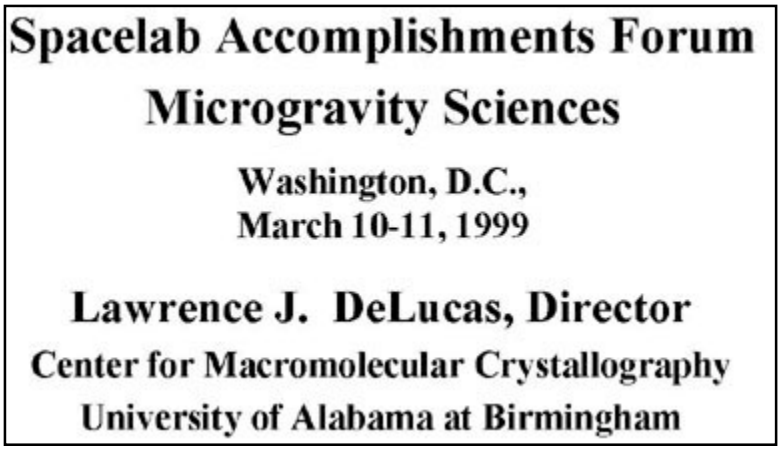


Figure 1. Introduction.

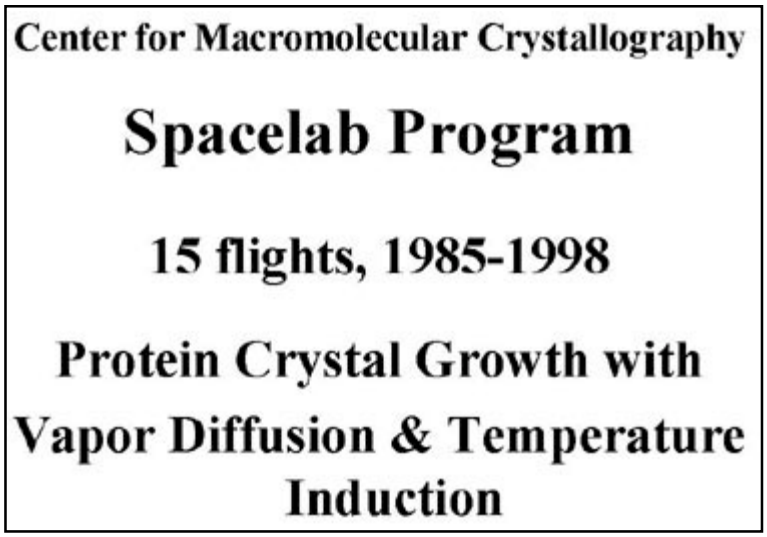


Figure 2. Topic background.

I'm the director of one of NASA's 16 commercial space centers (Figure 3). There is a lot of science to what we do. I want to just mention that, because you will see that everything that I talk about is with a goal in mind, and that goal is to produce better crystals so we can in fact impact structural biology and also, as you will see, develop new drugs.

We have flown protein crystal growth experiments on 15 Spacelab flights and we have flown protein crystal growth experiments on 37 Space Shuttle flights (Figure 4). I don't know of any other science experiment that has flown that often, but clearly you will see that flying often, and having the access to this environment, is a big advantage. We have a simple experiment, so we could fly often. All the science that you have heard about that happens in a module here in the last two days, to really make tremendous progress — we see so much potential — you have to do it every day. This is not like the Hubble telescope where you put this thing up and you could wait 20 years and it's still going to yield tremendous value. This kind of science is moving rapidly on the ground. In order to really be of value in space, we have to move rapidly. We can't do one experiment, wait five years and do another. We have to do it often, and it's



Figure 3. Research center.

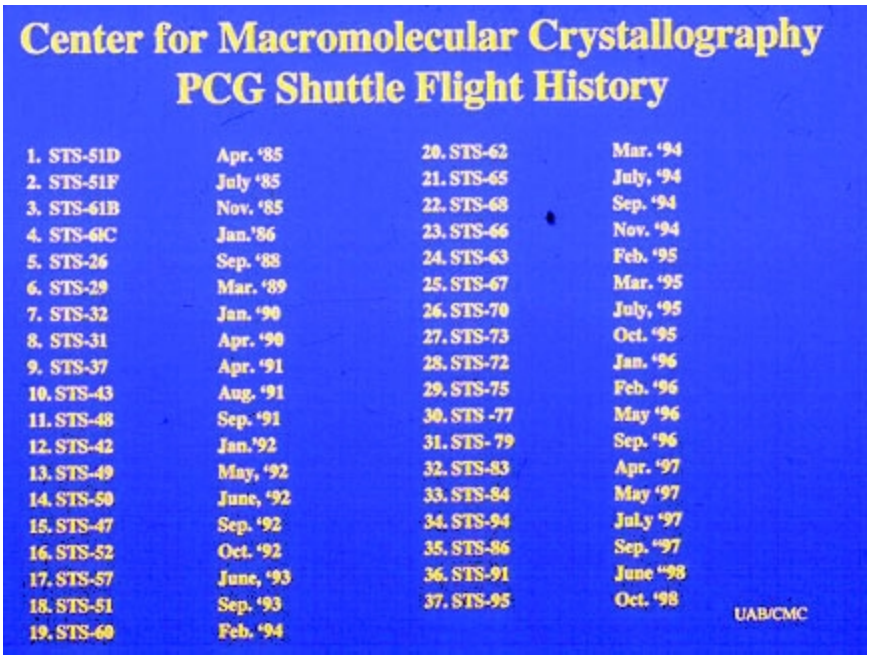


Figure 4. CMC flight history.

because I've been lucky enough to fly these experiments this often that I have a lot of wonderful stories to tell you.

We have flown two different types of experiments, vapor diffusion and temperature induction. I should mention why temperature induction works. Well, first, Franz Rosenberger, formerly a small molecule crystal grower, told me, "Larry, if you really want to control a crystal growth process — and that is in fact the key to getting better crystals on Earth or in space — the best way to do that is by temperature, at least with small molecules." We didn't know if you could do that with proteins. In the protein data banks there have been 18 proteins in the history of crystallography crystallized simply by changing the temperature. To do that, it means the protein solubility has to change when you change the temperature. Most biochemists will tell you it's not going to happen. Well, we know they are wrong now, thanks to NASA funding.

We built two different systems for space. It was this information — this is the work of other people, Ravi Lal and I believe Bill Witherow from Marshall Space Flight Center are involved in this research — that really got me excited (Figure 5). It showed that in a gravity-type environment you have a fluid flow, a

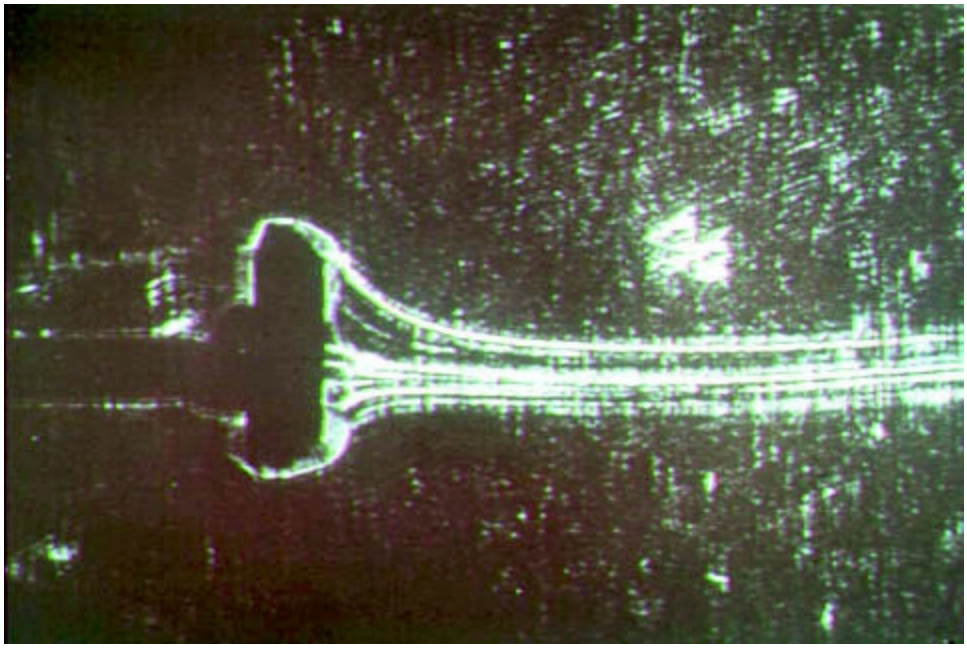


Figure 5. Fluid flow plume in a gravity-formed crystal.

plume that comes off the top of a crystal. If you do the same experiment in space — this is with interferometry — you can see the plume doesn't exist, but as you deplete the material around the growing crystal, it changes the optical characteristics and you get a new ring forming (Figure 6). It's a quiescent environment to grow a crystal.

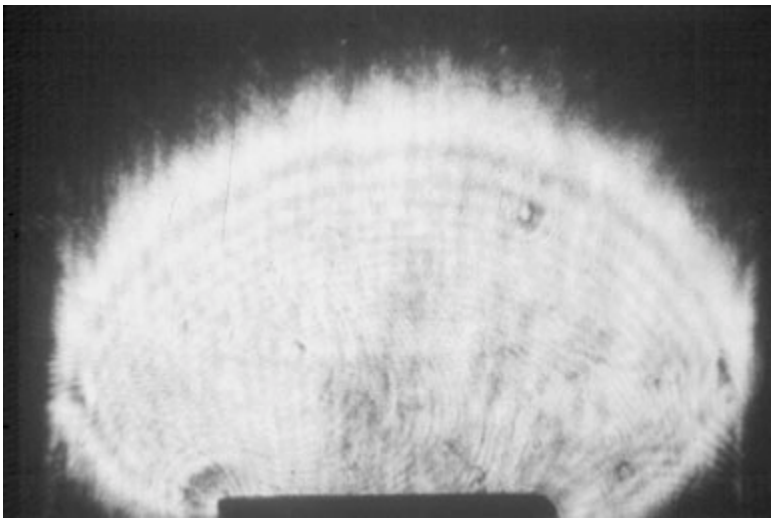


Figure 6. Quiescent growth crystal.

Mark Pusey said, "Will it happen with proteins?" Because in a protein, density of the crystal versus the solution is not as dramatic as in small molecules, and everyone said it won't. Well, Mark has a lot of data with lysozyme attached to a string. Sure enough that plume exists and it's moving up at a very rapid rate.

Why grow protein crystals in space? Well, typical success rates on Earth of growing protein crystals today are probably three out of every ten projects that we try to crystallize, we obtain crystals of high enough quality to go forward. That's why we need to look for other avenues. If you ask what parameters affect a crystal, there are so many, and probably many more than I know, and maybe the only one where space plays a role is convection. If the other parameters are not right, then microgravity won't help. There have been many experiments put up by my laboratory and others where the protein wasn't pure, wasn't homogeneous; people flew membrane proteins with lipid randomly attached to it; and sure enough, they didn't get better crystals.

The statistics that you see today for space research and how much it benefits protein crystal growth is right at about 25 to 30 percent success ratio, but a lot of that is influenced by all the other factors not being controlled. Today, again, a lot of the investigators being funded via NASA and other space agencies are making sure that we have these factors optimized so we can better understand their role, and my lab is doing that very same thing.

So, why go to space? Well, it will reduce these convective flows; we will minimize surface contact with the protein. Our first experiment had protein drops hanging on the tips of syringes because crystals like to nucleate off surfaces, and we don't want crystals attached to surfaces (Figure 7). Protein crystals are like an ordered jelly. If you touch them, they fall apart, and we can't do that. We have to have single beautiful crystals. Containerless crystal growth is very valuable. You heard Gene [Trinh] and some of the applications he talked about. If we could do that on a large scale, it's the best way to do containerless crystal growth as long as you are not overly vibrating the solution. On Earth with Gene's system there is too much vibration, but in space you don't have that, because the amplitude of the sound levels is diminished tremendously in the vibration frequencies. Finally, protein crystals either sediment or float to the top. As they do, they tend to get stuck together, and we must have single crystals. So we thought there were three nice advantages for going to space.

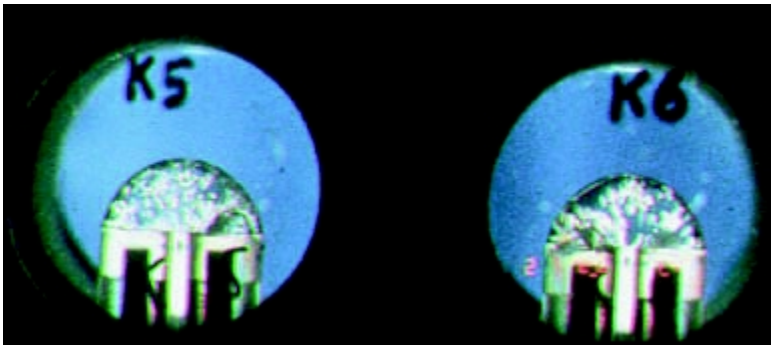


Figure 7. Crystal growth off of syringe tips.

If you look at a summary of the 15 Spacelab missions starting with STS-42 (Figure 8) you are looking at our candidate proteins, and they didn't all come from my lab (Figure 9, Figure 10, Figure 11, Figure 12, Figure 13). I think the really valuable part of my program is that the proteins that we put up in space come from investigators all over the world. Many of those investigators are not funded by space agencies of any kind. They simply want better crystals. They come from universities and pharmaceutical companies. When the crystals come back, we give them to those investigators. They go back to their lab and they do the analysis and they simply have to tell me are they better or not and prove it with the data. So it's a very

objective opinion, and you're seeing examples of the proteins that came back producing data from that one experiment in space that was better than the best crystals ever grown on Earth by any method. That is the criteria we use for everything I'm going to show you. You can see the protein and you can see the application to the right.

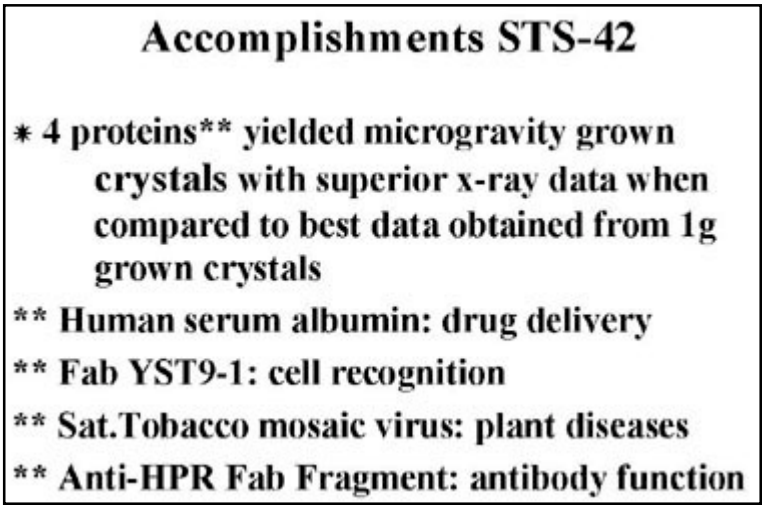


Figure 8. Data summary, STS-42, part 1.

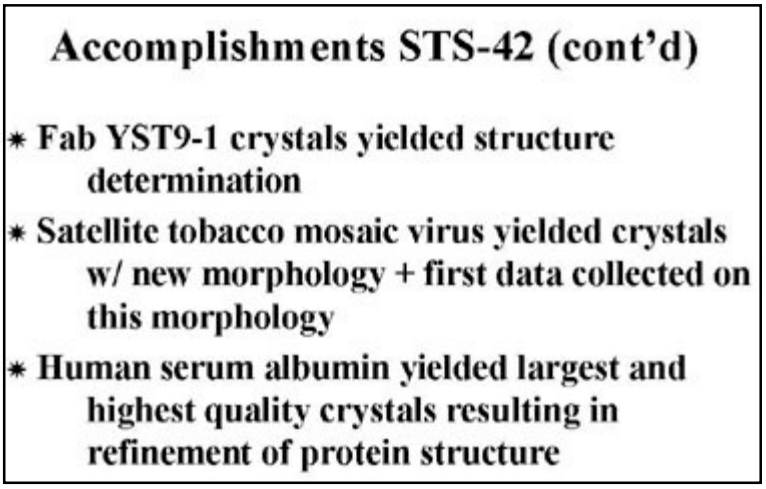


Figure 9. Data summary, STS-42, part 2.

Spacelab

Flight	Target	Disease/ Process/ Study
STS 42	Anti-HPR FabFragment	Antibody function
	Fab YST9-1	Cell recognition systems
	Sat. Tobacco Mosaic Virus	Plant diseases
	Human Serum Albumin	Drug delivery
STS 47	Epidermal Growth Factor	Cancer
	Lysozyme	µg effect on crystal structure

Figure 10. Spacelab flight data summary.

Spacelab (cont'd)

Flight	Target	Disease / Process / Study
STS 50	Malic enzyme	Parasitic diseases
	Factor D	CV disease, heart surgery
	Canavalin	Protein engineering
	HIV Reverse Transcriptase	HIV & AIDS
	Alpha Thrombin	Blood clots
	Prolyl Isomerase	Transplant rejection
	Alpha Interferon	Chronic hepatitis B & C
	DD-ligase	Antibiotic
STS 52	Alpha Interferon	Chronic hepatitis B & C
STS-62	JEL42 monoclonal antibody	Antibody function

Figure 11. Spacelab flight data summary, part 2.

Spacelab (cont'd)

Flight	Target	Disease/ Process/ Study
STS 66	Human Serum Albumin	Drug deliver
	Malic Enzyme	Parasitic disease
	Parathyroid Hormone	Osteoporosis
	Aldehyde Reductase	Diabetic complications
	Calicivirus	Dev. vaccines & antivirals
	Ribonuclease S	μg effect on crystal structure
STS 67	PEP Carboxykinase	Diabetes
STS-68	Alpha Interferon	Chronic hepatitis B & C

Figure 12. Spacelab flight data summary, part 3.

Spacelab (cont'd)

Flight	Target	Disease/ Process/ Study
STS 73	Insulin-Lys-Pro	Diabetes
STS 94	PEP Carboxykinase	Diabetes
	Proteinase K	Atomic structure resolution
	NAD Synthetase	Antibiotic
	5S rRNA	Protein biosynthesis
	Hyaluronidase	Vaccine vs. bacteria infection
	Glyceraldehyde-3-P	Chagas' Disease
	Dehydrogenase	
	Lectin KM+	Inflammation
	Glucoamylase	Industrial pplication:conversion starch to glucose

Figure 13. Spacelab flight data summary, part 4.

This was the most important space flight, because I flew on it. You can see the examples. There are a number of proteins, and we also had the big payload on this. It's not because I flew; we flew 31 proteins on this flight, but this is what came back producing better data. Here is more from other flights (Figure 14).

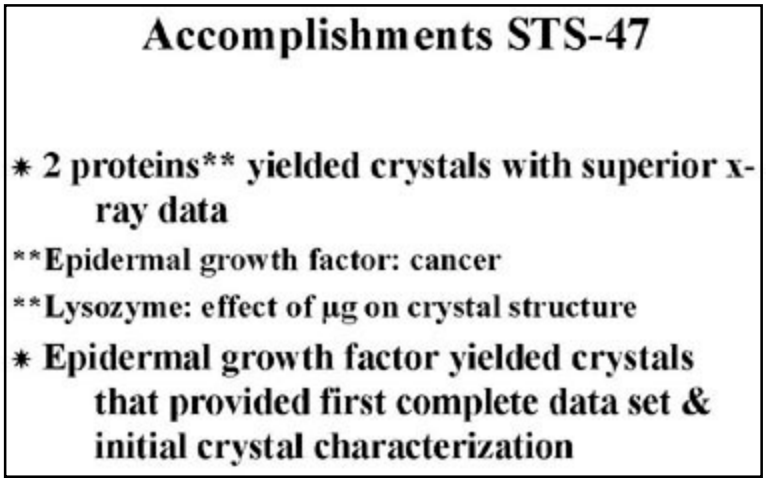


Figure 14. Accomplishments on STS-47.

Where you see only one, we only flew one, and we flew it with temperature induction (Figure 15, Figure 16, Figure 17, Figure 18, Figure 19). That experiment has now flown, I believe total on all the Shuttle flights, about ten times and only once did we not come back with crystals better than the best ever produced on Earth. Temperature is, in fact, a great way to grow crystals, and we are finding that it is applicable to a number of proteins.

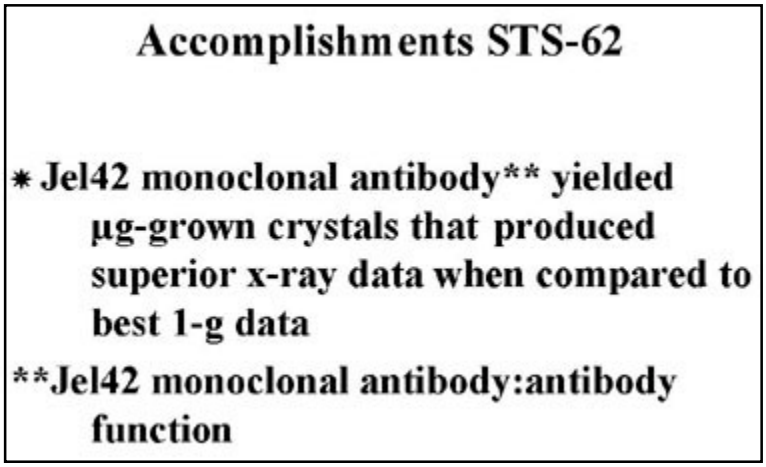


Figure 15. Accomplishments on STS-62.

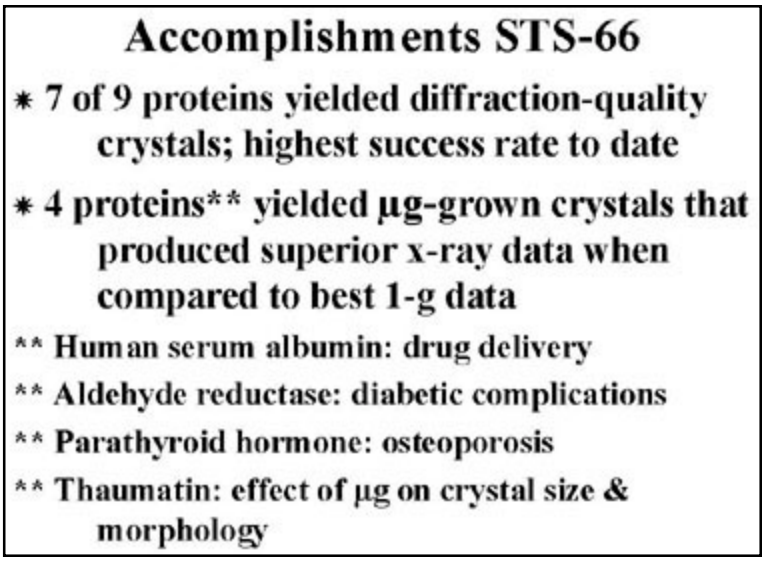


Figure 16. Accomplishments on STS-66.

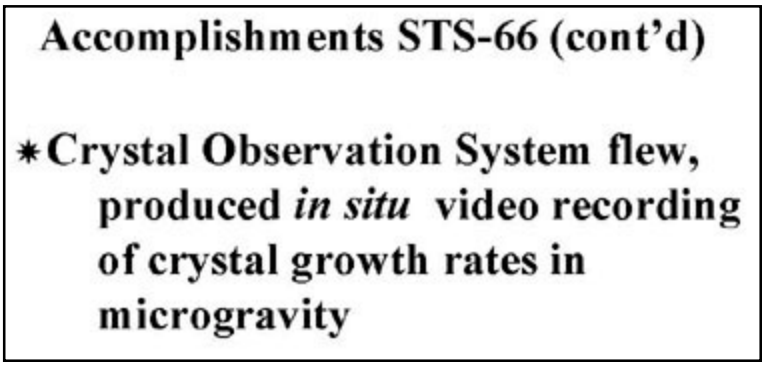


Figure 17. Accomplishments on STS-66, continued.

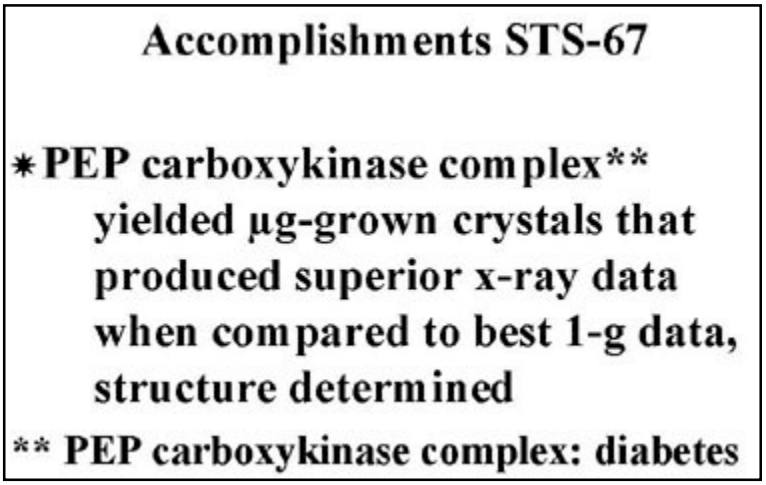


Figure 18. Accomplishments on STS-67.

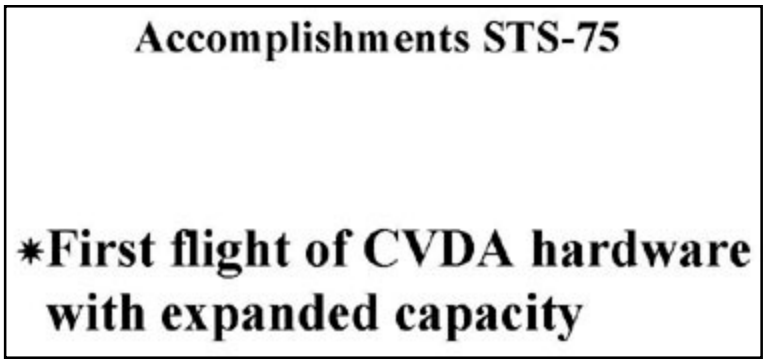


Figure 19. Accomplishments on STS-75.

Just from my laboratory, these are the publications and the preceding publications in journal articles, a total of 47 (Figure 20). All those other investigators have published many papers, and I couldn't get that together fast enough for this proceeding. I'm sure over 100 papers have come from this work.

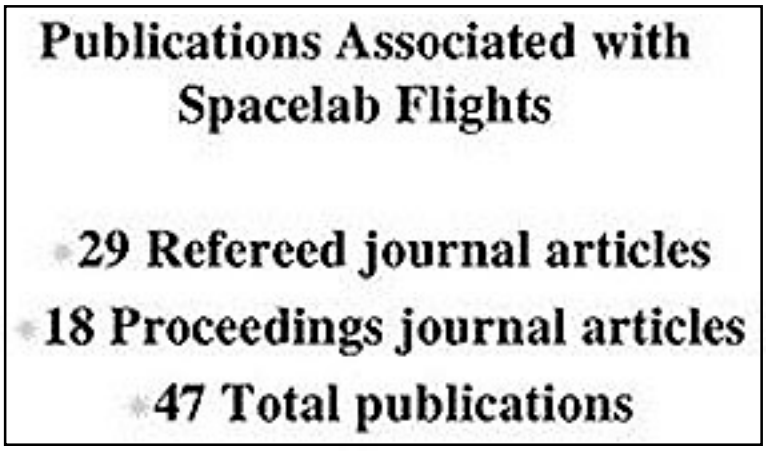


Figure 20. Publications from Spacelab flights.

On STS-50 we established the value of optimizing crystal growth experiments in space (Figure 21, Figure 22). Previously, what we did in space is what we thought would work, and the conditions for the best

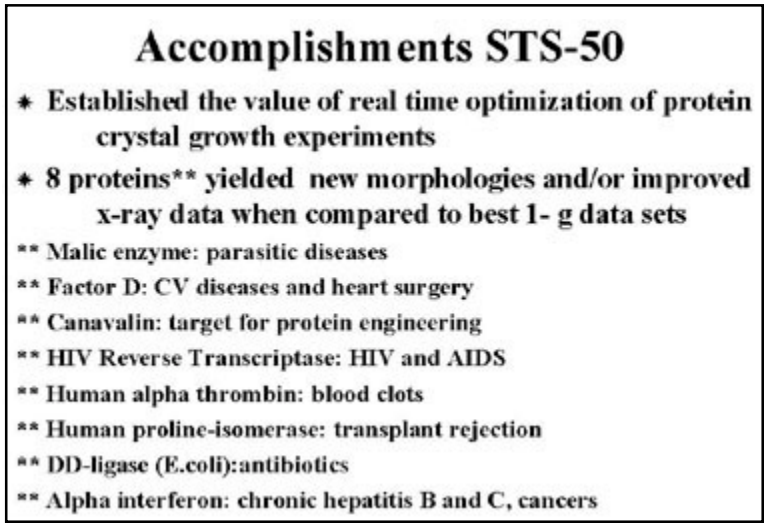


Figure 21. Accomplishments of STS-50.

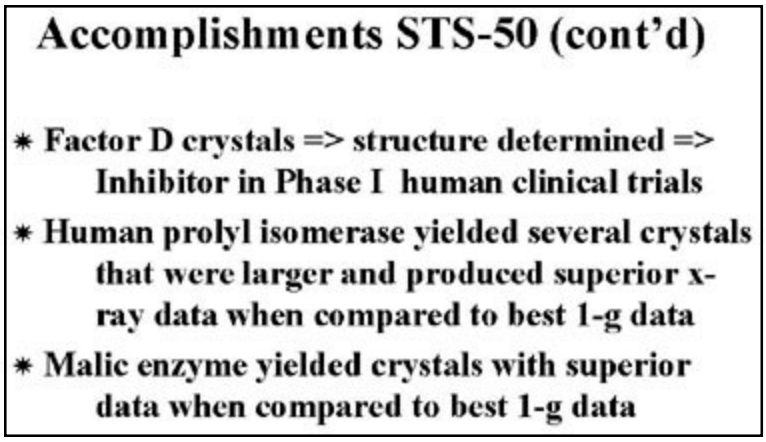


Figure 22. Accomplishments of STS-50, part 2.

crystal in space are clearly different than the optimal conditions down here. Sometimes we just missed it. The purpose of my flying in space was to sit there after three days, look at what happened, and then optimize the experiment by changing the chemical composition of new experiments.

It didn't work as well as I would have liked, because after three days nothing had nucleated… not one protein out of 31 proteins. On Earth they all would have nucleated. In all the controls they did, and many of them would have been fully grown. Why is that? Well, without that convective stirring, nucleation does not happen as quickly. So I was pretty depressed day three, and I was real worried I was going to come down with nothing. But day four it all started to happen. Unfortunately, it was so slow that it was difficult to see what I should do to optimize those conditions, and only for a few proteins was I able to do that, but those that I did it with produced the best crystals ever, on Earth or in space.

I'm convinced when we have a Space Station where we can set up experiments and look at the results — the only way to analyze a crystal once it's grown is with x-ray data to know about the quality — but once we do that, we'll be able to set up new experiments and optimize them and improve that success rate dramatically.

Eight proteins yielded new morphologies or improved x-ray data, and they are listed here (Figures 21, 22). You can see the applications.

The structure of Factor D, which is our own project, has resulted in phase 1 human clinical trials for a drug that was developed by a pharmaceutical partner based on that structure (Figure 23). The structure for one crystal form was determined with space and Earth crystals. Space provided additional crystals of this particular crystal form that was difficult to produce on Earth. It should be noted that other crystal forms, grown on Earth, were also used for structure determinations of this protein. Today a drug is in human clinical trials for complications from open heart surgery, and eventually it will be used as a deterrent to stroke formation.

This is me working in the Glovebox where I would optimize the crystal growth (Figure 24). Our engineers in the Center developed this hardware. We build everything right at UAB.

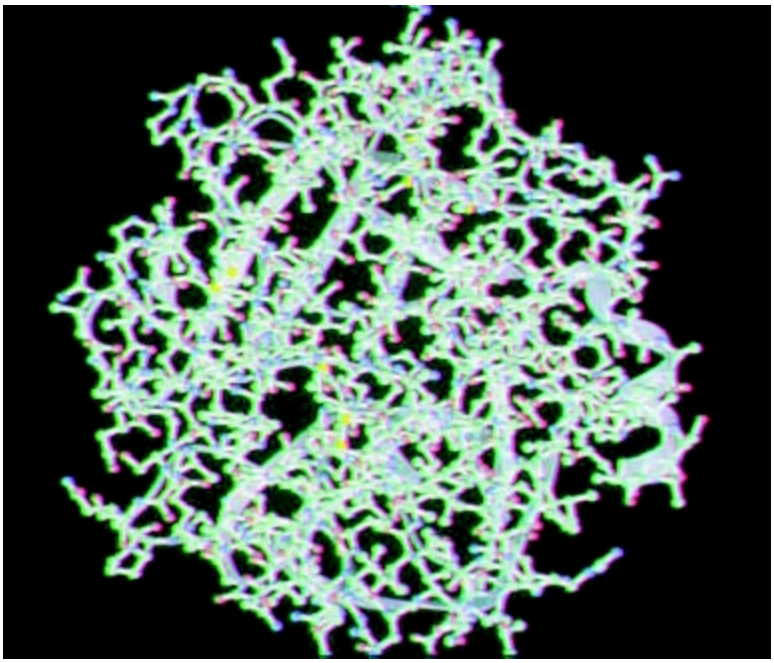


Figure 23. Structure of Factor D.



Figure 24. Dr. DeLucas working in the Glovebox.

I even mounted crystals up there and I mixed solutions, and I learned that not only does the nucleation process take a long time, but mixing is not easy. On Earth you take the two solutions, put them together and just stir it with the tip of the needle. In space, when I did that, because we were on a hydrophobic surface, the drop moved with my needle; I couldn't stir it. So I had to suck it up into the syringe and then extrude it to actually mix the solutions.

This is one of the crystals, the Factor D crystal, which was the largest one ever grown (Figure 25). It was so long, about 1.6 millimeters, that we collected several data sets down the long axis. It's with that crystal, combined with other, Earth-grown, crystals, that we solved the structure of this crystal form of Factor D.

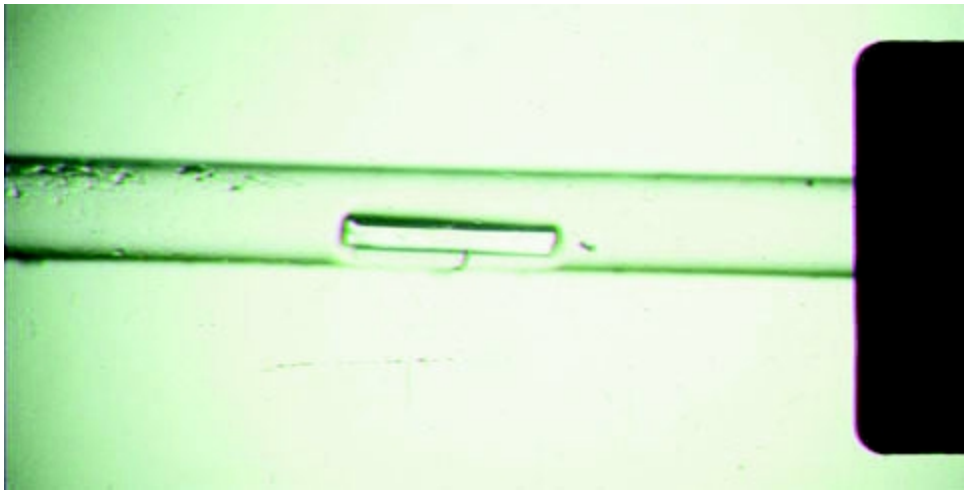


Figure 25. The largest crystal ever grown of Factor D.

This is malic enzyme flown by Upjohn. They had worked several years on this project and could not get data to three angstroms, which is critical to begin to solve the structure. So we flew it in space (Figure 26).

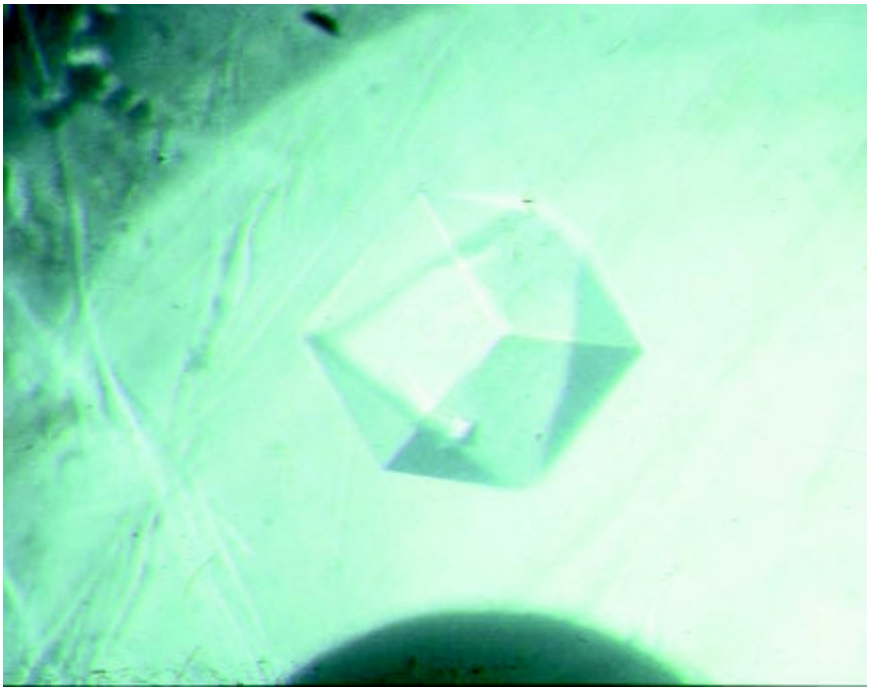


Figure 26. Malic enzyme crystal grown in space.

This is one of about 30 crystals that came back. They are 0.2 millimeters on an edge. Upjohn, in their lab their best crystals were 0.85 millimeters on an edge. We compared their best and biggest crystal with the space crystals.

This is the data, or a slice of it, from space crystals. Here is the best data set ever collected at Upjohn (Figure 27). The further you go to the right, the higher the resolution. You can see there was a 40 percent increase in data, in spite of the fact that the space crystal was much smaller.

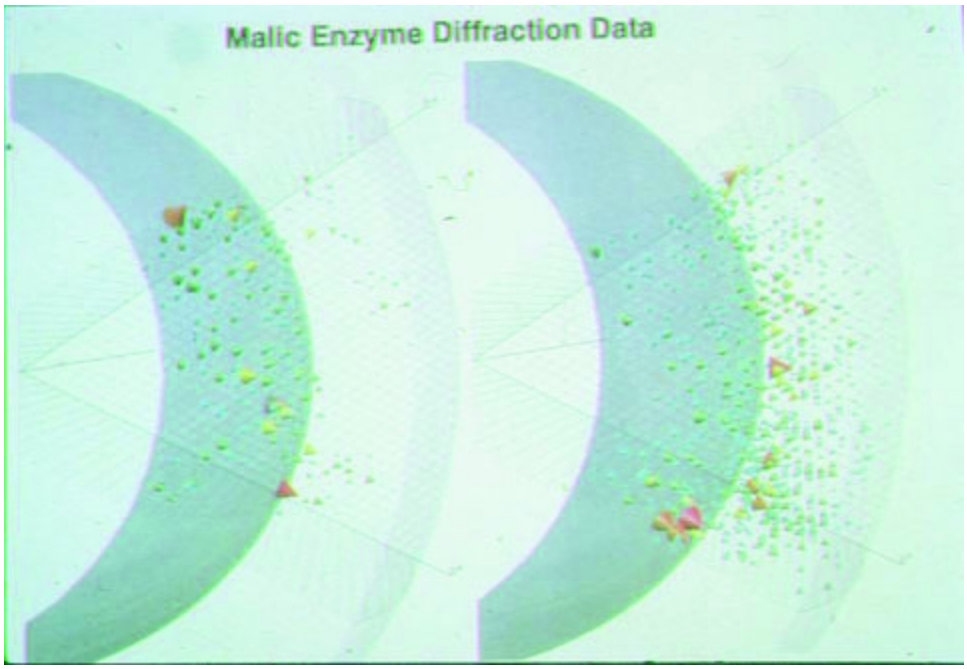


Figure 27. High resolution data from Upjohn.

We also did large-scale temperature induction crystal growth. It was Schering Plough that wanted us to do that, but it was people like Franz Rosenberger that had told me to use temperature, because that's going to really yield some wonderful benefits. On Earth, if you change the temperature of a solution, you're really going to have convective flows. In space, as long as you don't have a free surface, you're going to minimize all flow. So only the movement, random diffusion of the molecule to the surface is going to allow that crystal to grow, and that is just what you want.

From those experiments that we did with Schering we obtained the best crystals ever (Figure 28). Those crystals led to in vivo primate tests. What they were doing is developing a time release formulation for alpha interferon. That inspired Schering, to continue development of a new pharmaceutical that is based on time-release. I will show you why.

Accomplishments STS-52

- Large-scale temperature-induction crystal growth method
- Corporate partner, Schering Plough, provided $5 million worth of alpha interferon to support microgravity experiment
- Large quantity of large crystals
- In vivo primate tests demonstrated use of crystals as time-release formulation
- Sample & data provided enabling technology for further research and development on ground
- Crystals were useful starting point to produce crystalline time-release protein pharmaceuticals

Figure 28. Accomplishments on STS-52.

This is what we grow the crystals in (Figure 29). They are in long bottles that sit in the container. The biggest bottle holds half a liter of protein. The metal end sits against the cold plate of the incubator. In a typical experiment on Earth, you start at 50 degrees. You go up to space, and now the incubator ramps temperature down towards, say, 22 degrees. So you get a temperature gradient down the long axis of the bottle, and crystals begin to grow.

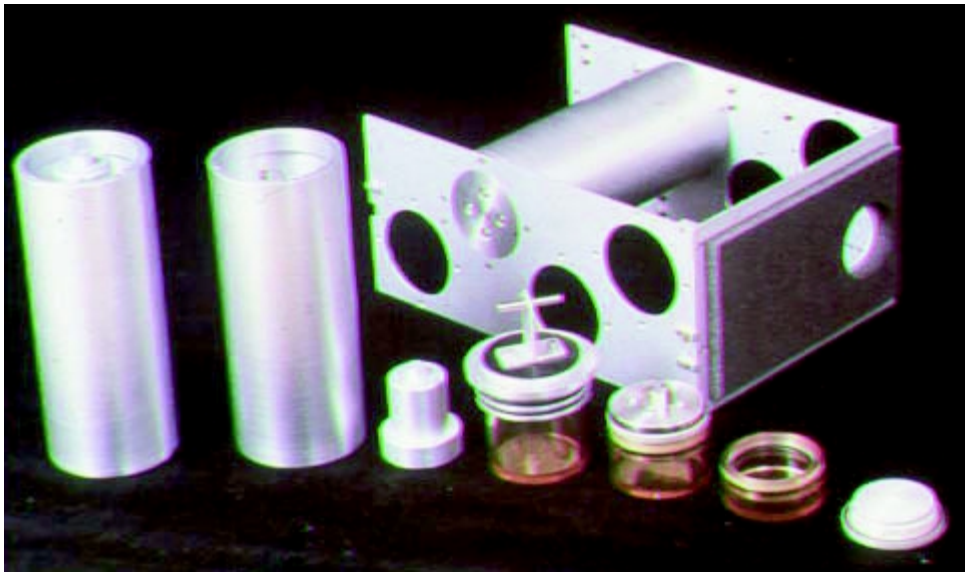


Figure 29. Crystal growth hardware.

We tried it first with bovine insulin just to test the hardware, and we flew it on three Shuttle flights. This is what we were getting on Earth (Figure 30). I didn't change the power of the microscope. This is what

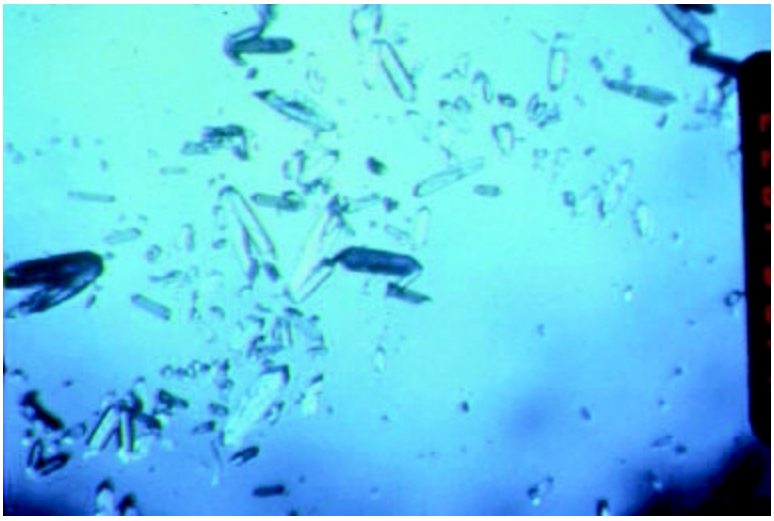


Figure 30. Terrestrial bovine insulin crystals.

came back from space (Figure 31). They diffracted half an angstrom further in resolution. If you look at all the data from those three Shuttle flights shown here, this is the big bottle, half a liter; then the next one was 200, 100, and 50 milliliters. You will notice some trends here (Figure 32). The bigger the bottle, the bigger

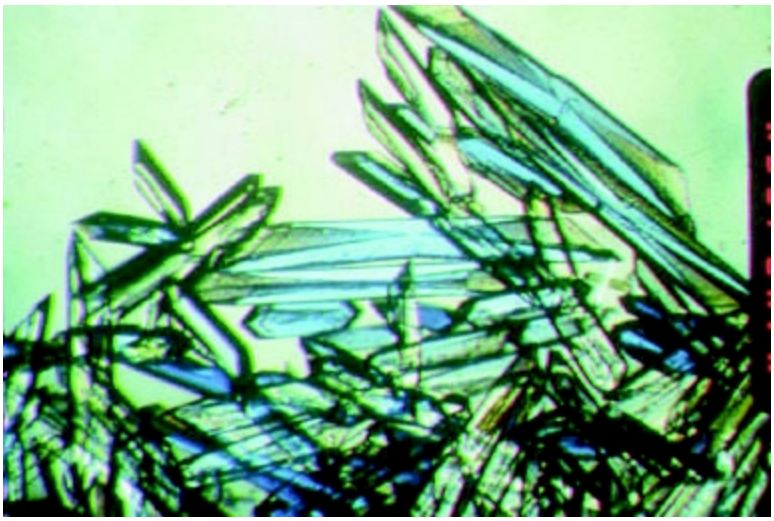


Figure 31. Space-grown bovine insulin crystals.

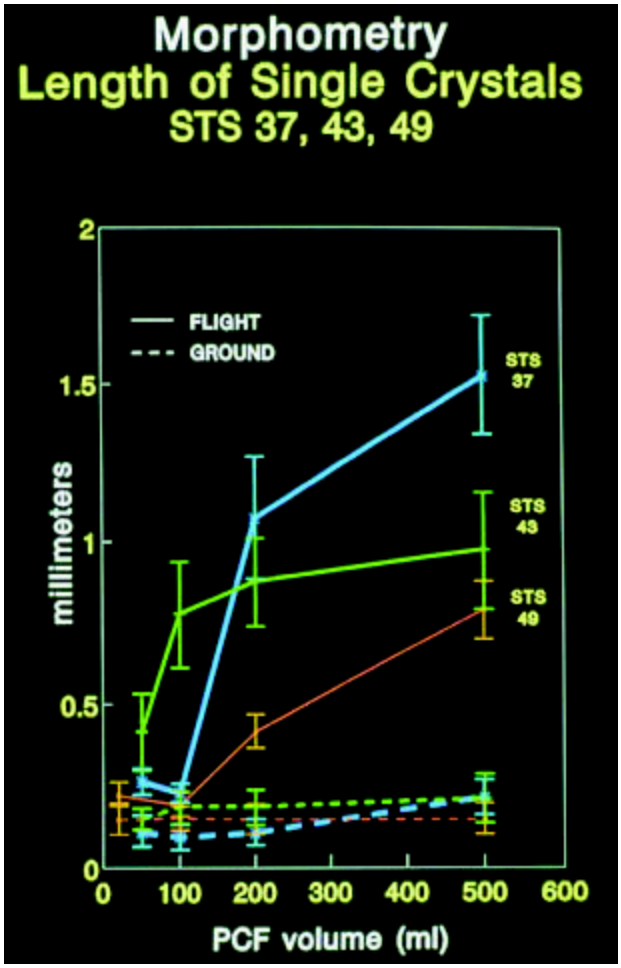


Figure 32. Flight data trends.

the crystals. The solid lines are the space flight data; the dotted lines are what we got in the Earth control samples. That was one trend.

I should note that all the data shown in the graph from space was from the crystals that were free floating — there were thousands of crystals attached to the surface of the bottles. If I plotted that data, they would actually be down below the dotted lines. I scratched my head trying to understand this. Gene Trinh and Joe Prahl used the theory of fluid flows to try to make sense of the data. Sure enough, I think there was an explanation. We didn't have a camera to prove this, but what we determined, number one you can do a calculation: how fast does insulin move? Which is what we were flying here, on Earth. How long does it take it to move just four centimeters? Because of buoyancy induced convective flows, it moves four centimeters in about six hours. How fast does it move four centimeters in a microgravity environment? Sixty days. So a crystal that is stuck to the surface is going to deplete the protein around it, and it takes so long for the next protein molecule to get to the surface, they didn't get large.

The crystals that were free floating have a density that is a tenth different than the solution they are in, and they are being pulled on by microgravity. As a result, they are moving an order of magnitude faster than protein randomly diffuses. That's how we explain the free floating crystals being so large. Then if you look at where the G vector was on those Shuttle flights, it was on about a 45 degree angle down the long axis of the bottles. So we are guessing that they could move further the longer the bottle, and that is why some of the crystals were larger than others. It certainly wasn't because we ran out of protein. We had much more protein than we needed.

This told me something about the Shuttle and why maybe we're having failures. Forty percent of all the failures from the Shuttle are not because we didn't obtain good crystals; it's because they were so small we couldn't even expose them to x-rays; we couldn't even mount them. I think it's because those crystals probably had a density closely matched to the solution or were attached to the tip of the syringe, and as a result, they did not get enough protein to grow large enough in a 10-day Shuttle period. On Space Station that is going to dramatically change. We'll be able to let those crystals grow a month or more.

We already know this from the work of people like Dan Carter and Alex McPherson on Mir — they have come back with crystals a centimeter in size. In the whole history of crystallography there are only about seven or eight proteins we've been able to grow to that size. The advantage of that is they are so large you can't do x-ray crystallography, but you can do neutron crystallography, and with that, for the first time you can actually locate the positions of all the hydrogen atoms. That is very important in structural biology, because that is what imparts the function; it's hydrogen binding interactions, and it is also critical in drug design.

We chose space crystals, many of which were not bigger than the little Earth crystals, and in spite of that the x-ray intensity of the data was sometimes triple. It tells you the quality of the crystal must be better.

On STS-68, protein crystal growth was performed by vapor diffusion and temperature induction (for alpha interferon). Here's why Schering was interested in this (Figure 33). Today, if you have hepatitis C, the typical treatment is to administer alpha interferon. The way they do it is they inject it into your blood. You can't take it in your stomach because the protein will degrade. They have to inject it about every three hours because the dose level that you want is in a very narrow range. Anything above that you get side effects. One of the big side effects is depression.



Figure 33. Accomplishments on STS-68.

So you have these multiple injections you have to have all day to treat hepatitis C. Not a good way to care for patients. Plus they are not doing real well in terms of side effects. If you could have something that is slowly released via time release, like insulin, over a long period of time perhaps you could stay in the good region that is effective dosing but doesn't have the dramatic side effects.

What Schering couldn't do on Earth is grow crystals that were shaped like balls. They wanted crystals 13 microns in each dimension. That's the optimum size to inject into your blood. On Earth, when you try to grow crystals of alpha interferon, they grow as big flat plates. I told a researcher at Schering, "We've seen in space that we tend to get crystals that are more bulky grown equally in each dimension, and there is a lot of theory that explains why that would be true." So he got excited. They gave us $5 million worth of alpha interferon to fly in those bottles. We flew it, and got the size they wanted. So that is what went into primate studies. The crystals were right in the optimum region to give you an effective dose, with fewer side effects, and now the ones they have tried have doses that stayed pretty level past a full day. That means you inject one time per day to treat the patient.

What has this led to? A market in space? No. Schering said, "We want to find out how to do this on the ground", and via micropheres they are now, through slow injection, treating patients with a slow release of the alpha interferon. This is what got them excited, that it could work, and they published two papers to say this.

We also realized that we want to understand the process and control it. So using a laser, we could tell right when two molecules start to come together to form a crystal, and then right at that critical time change the temperature rate. So we control the process pre-nucleation and post-nucleation. Talk to people like Franz Rosenberger and Alex Chernov and that is what they'll say you need to do to grow good crystals. So we built this hardware. We flew it on STS-73, working this time with Eli Lilly, flying human insulin that was a special type that they wanted to market. It is marketed today, and it's called "Humalog".

What Eli Lilly wanted was very high resolution data of this structure, because they actually changed some of the amino acids in it (Figure 34, Figure 35). They couldn't get that from Earth. We got these crystals from space. We gave them a data set that was an improvement over what they had on Earth. They were also trying to develop a long acting insulin (Figure 36). This is what they had for the crystals on Earth. This is

Accomplishments STS-73

* Over 80 individual experiments prepared on orbit
* First interactive communication between payload specialist and ground-based scientists by video downlink, electronic still camera image transfer and KCA file transfer

Figure 34. Accomplishments on STS-73.

Accomplishments STS-73 (cont'd)

* Large-scale temperature-induction protein crystal growth
* Insulin-Lys-Pro (Humalog®) with Hauptman Woodward Medical Research Institute & sample provided by Eli Lilly
* Obtained large quantities of crystals
* Established crystallization conditions for follow-on flight that yielded superior x-ray data when compared to best 1-g data

Figure 35. Accomplishments on STS-73, continued.

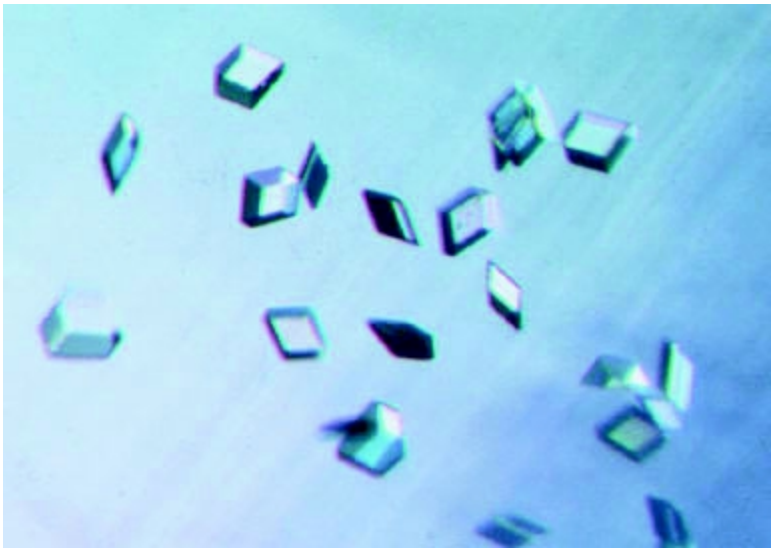


Figure 36. Insulin crystals.

where we ramped the temperature and the laser sees nucleation, and then we changed the rate of temperature and slow it down to slowly let the crystal grow once it's formed (Figure 37). This is what came back from space, the same power of the microscope.

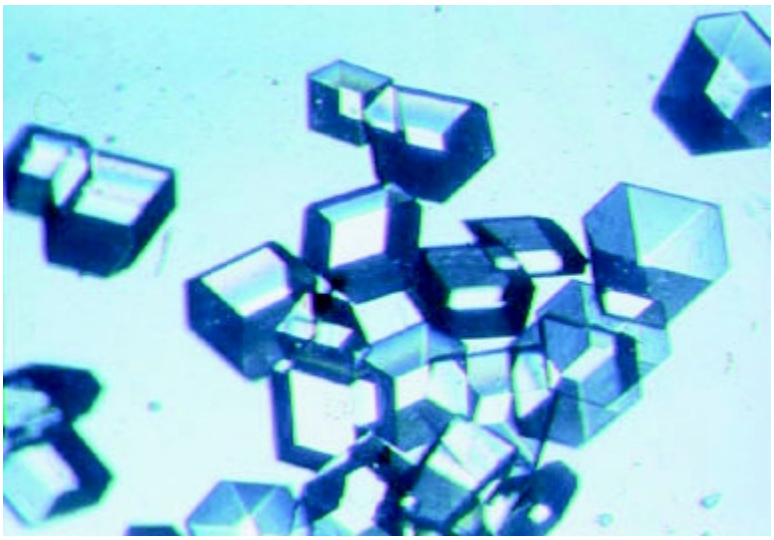


Figure 37. Space grown insulin crystals.

The important thing is, when you look at the electron density map, this is what a crystallographer sees (Figure 38). We have one molecule of an insulin hexamer that would go down below the floor, and another arm that would go up into the ceiling. There is one section of the map coming out and one going back. That's the drug in the crystal that makes it dissolve more slowly in your blood. There is also a section they interpreted as water. Well, from the space crystals they found there were actually two drug molecules in

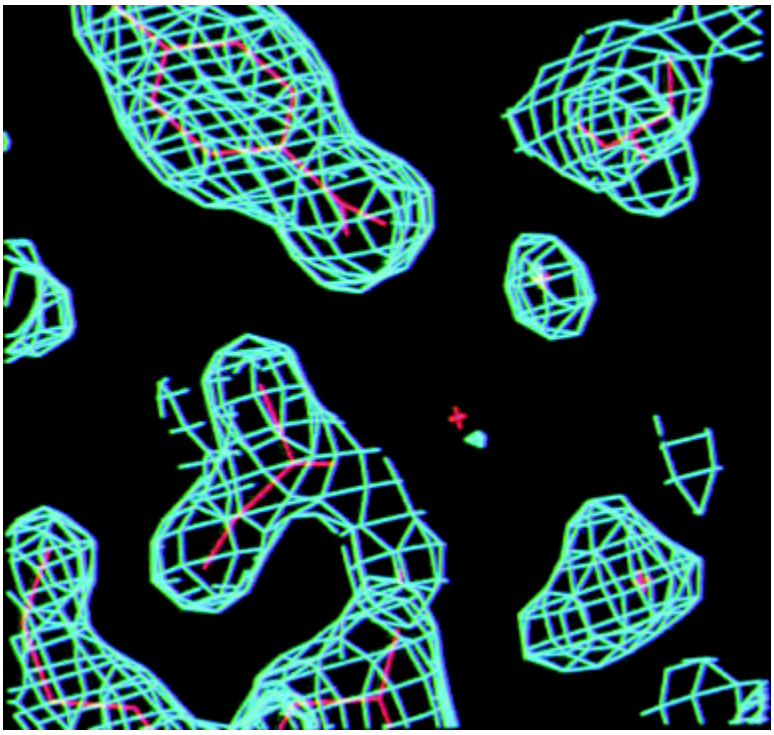


Figure 38. Standard electron density map of insulin.

that pocket (Figure 39). All the distances here changed between 0.2 and 0.4 angstroms. A dramatic difference. Now what they are doing is developing a compound that fits this whole pocket. The person working on this is a Nobel laureate and he testified in front of Congress about the value of that experiment. On STS-94, eight of ten proteins yielded diffraction quality crystals (Figure 40, Figure 41). They provided refined structures that were completed for four proteins now. This one right here was used in the development of an antibiotic, a new broad spectrum antibiotic. It is right now in animal clinical trials. The data from space diffracted to 0.8 angstroms resolution. The best we had before was 1.6 angstroms resolution, a dramatic increase in the amount of data. This is in pre-clinical, animal trials.

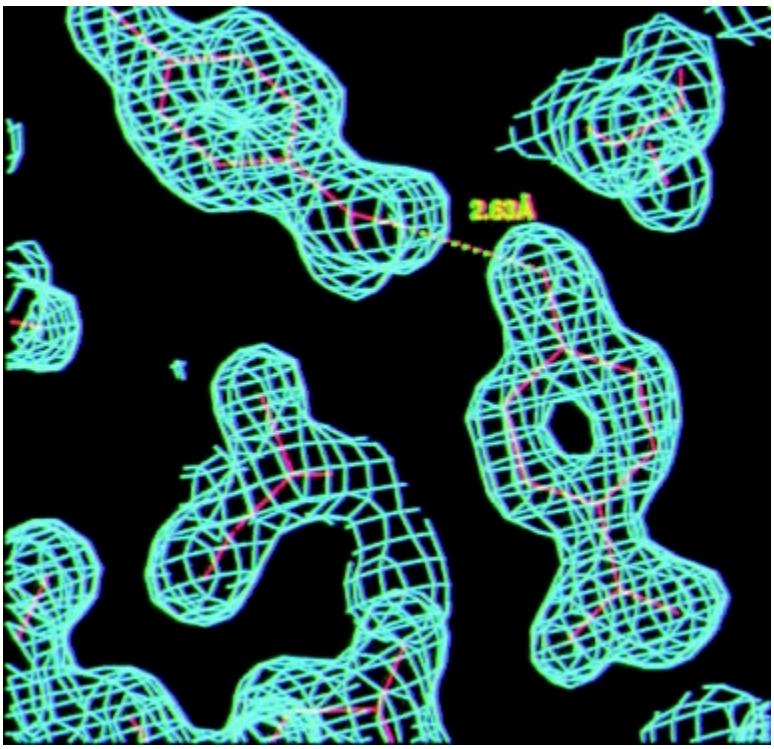


Figure 39. Electron density map of space-grown insulin.

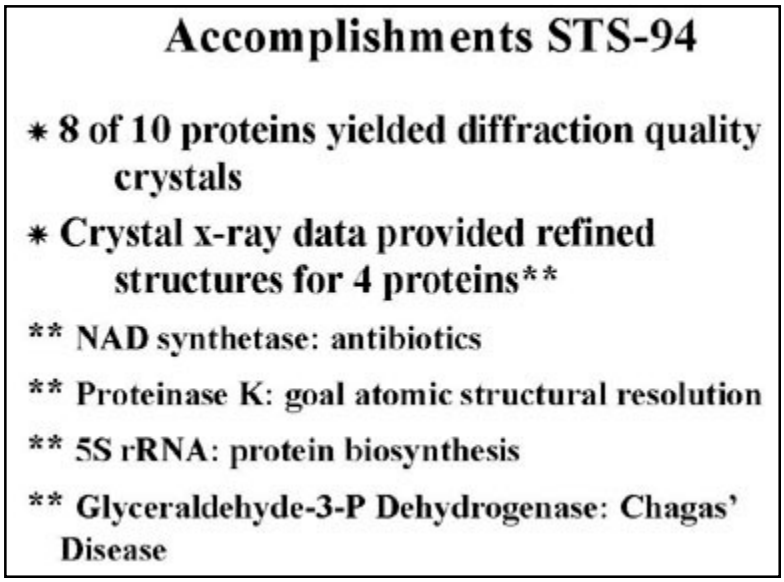


Figure 40. Accomplishments on STS-94.

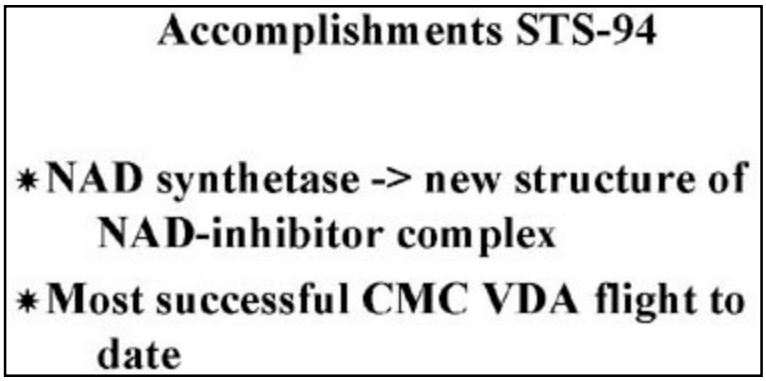


Figure 41. Accomplishments on STS-94, continued.

Some of this data is from way back from Franz Rosenberger's lab. He talked about how impurities and temperature spikes can affect a crystal and put large veils right in the crystal. People like Steve Durbin were doing atomic force microscopy (AFM), and they demonstrated how defects can form with the impurity rate going up or the rate of crystal growth increasing. All that has been very valuable. Today, because that technique (AFM) has improved, Alex McPherson is actually seeing this at the atomic level.

We are building a dynamically controlled protein crystal growth system. It is done and collecting data in our lab. We use lasers and high resolution video to control the whole process (Figure 42). What we want

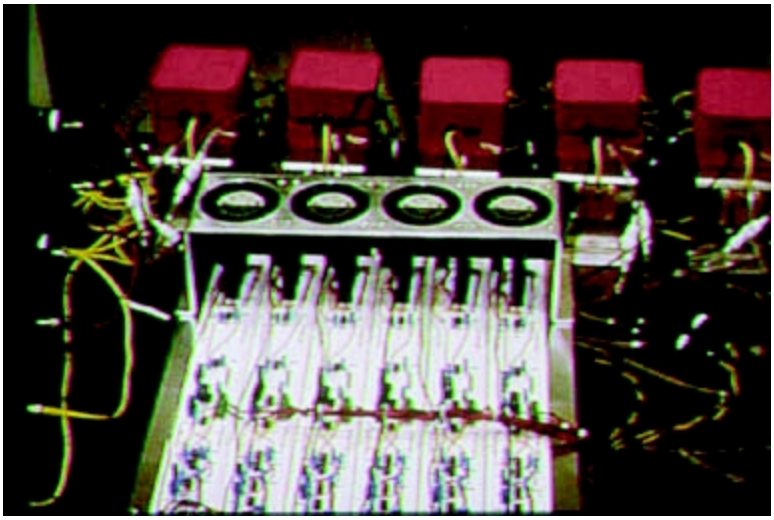


Figure 42. Laser and high-resolution video controls.

to do is get a crystal started, and then slowly grow that crystal. We are able to do that with this machine that, thanks to NASA, we have developed in our lab. There are 40 individual experiments simultaneously being controlled. The laser is looking at molecules coming together. We also have a similar one with 40 experiments for temperature induced crystal growth. Here is an example of what we have done with temperature (Figure 43). This is a profile of growing the crystals over four days, ten days, and 20 days, with the results. Show are the fourth day, the tenth day, the 20th day. It was 3.1 millimeters on edge, diffracted half an angstrom further in resolution. We are now building that system for space flight.

Bill Wilson does a lot of laser light scattering. He said the second virial coefficient could be a very important term, because it tells you how much a protein wants to associate with itself versus just being in solu-

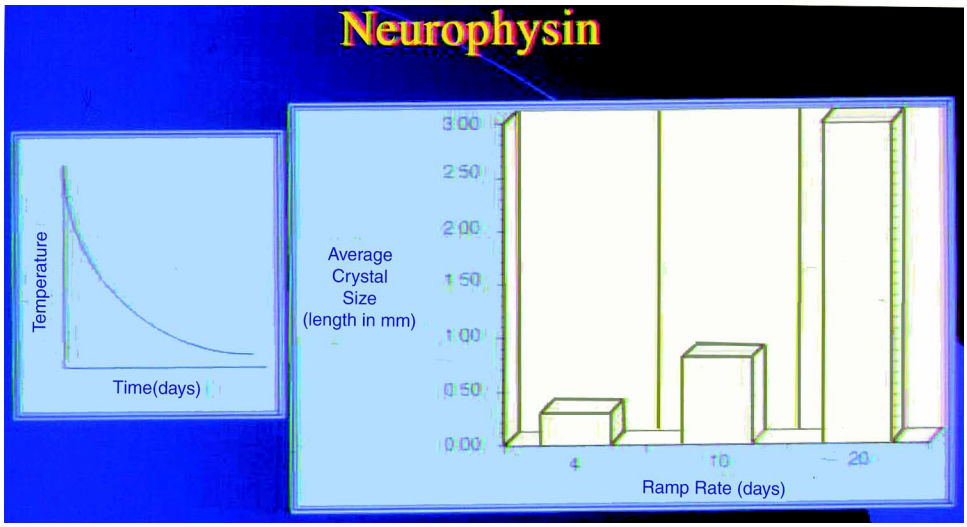


Figure 43. Profile of crystal growth with temperature controls.

tion. He thought he could use the second virial coefficient to study what would be good crystallization conditions. As a result, he said if you have good conditions, you ought to be close to zero or slightly negative; if it's going to stay in solution, it should be positive; and if it's going to precipitate, negative.

Alex McPherson, myself and Dan Carter gave him 20 proteins, four different conditions, one that we knew would make it crystallize if you concentrated it, three others that would either keep in solution or make it precipitate. He had to predict which was which in a blind study, and he came up with what he called a crystallization slot, that if the second virial coefficient fell in there, that would be where it would have a higher probability of crystallizing, and he was right on the ball with every one of those 20 examples (Figure 44). Then Bill said, if that is true and you remeasure the second virial coefficient in that slot at a different

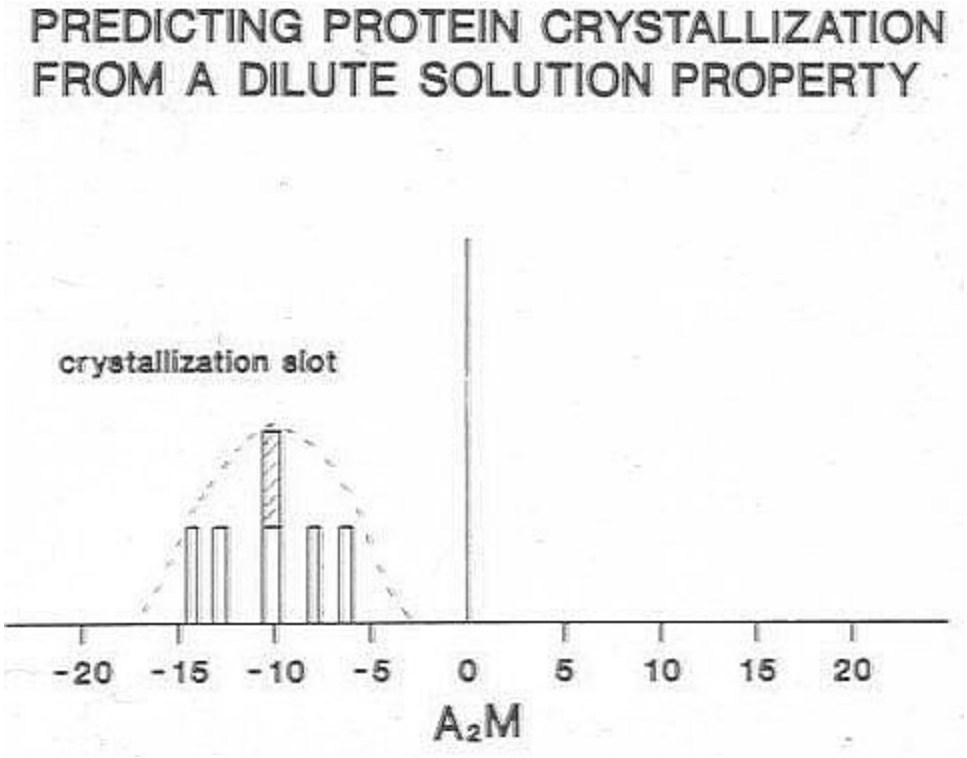


Figure 44. Laser light scattering identification of crystals.

temperature and you see a change in the value of the second virial coefficient for this lysozyme, it goes from minus 8 to plus 8, that means you probably can use temperature as a method to force it out of solution and crystallize.

With that, we have now studied several proteins and we are finding, yes, in fact there are new proteins at a specific ionic strength pH where a temperature change will change the solubility of the protein. It is opening a door to a whole new way to crystallize proteins and control the process.

NASA makes you think differently. For the Space Station, I want an x-ray machine, and NASA said, wow, that's impossible. You're not going to have eight kilowatts, which is what we have in our lab, to run this one and a half ton machine. NASA said if you want it, you'd better figure a way to do it smaller and with less power. So they funded us to do a feasibility study. Once we said it was feasible, they funded us to develop the ground technology.

Let me show you what has come from that (Figure 45). Working with a company called Bede Scientific Instruments, we developed a power source. It weighs 30 pounds and it requires 25 watts to generate a better beam than the rotating anode that uses eight kilowatts. This is the focusing technology. We are using just a commercial CCD detector, and it was built specifically to fit in a Space Station rack. This is the goniometer that houses it. Then the question is, who is going to mount these crystals. We either cryo-preserve them or mount them in capillaries, and it's a very delicate procedure. It's like doing corneal surgery. Well, we said we were going to develop a robot to do the whole thing. I wanted to do it telerobotically. Then I learned about lag times. I said, oh God, that's not going to be good. Well, we've done it robotically, and on a KC-135 we withdraw and mount and freeze a crystal in less than 20 seconds with an 85 percent success rate.

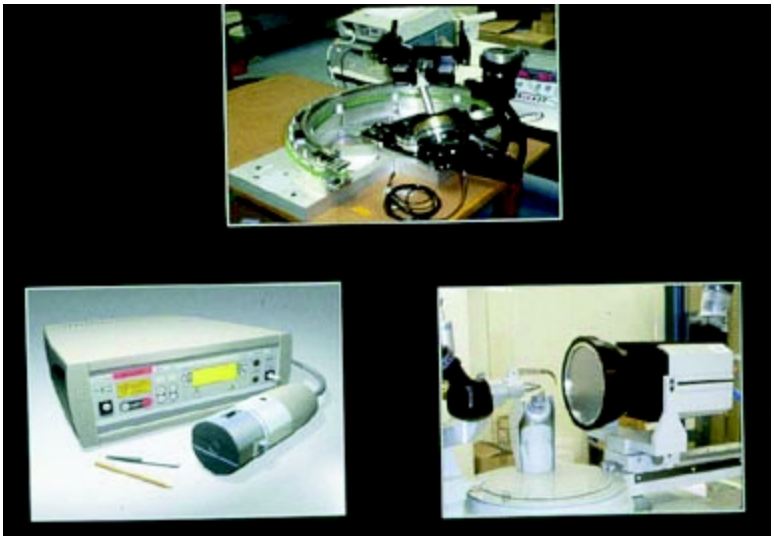


Figure 45. Crystal growth hardware.

This is a diffraction pattern, not from lysozyme, from a protease for the dengue virus (Figure 46). It diffracts to 1.7 angstroms. It's the best data set we have been able to collect, using this new machine.

This is what we developed (Figure 47). This little robot here goes down, sucks up the crystal, puts the syringe in there. There is an opposing syringe. Through a chain of commands it squirts the crystal in

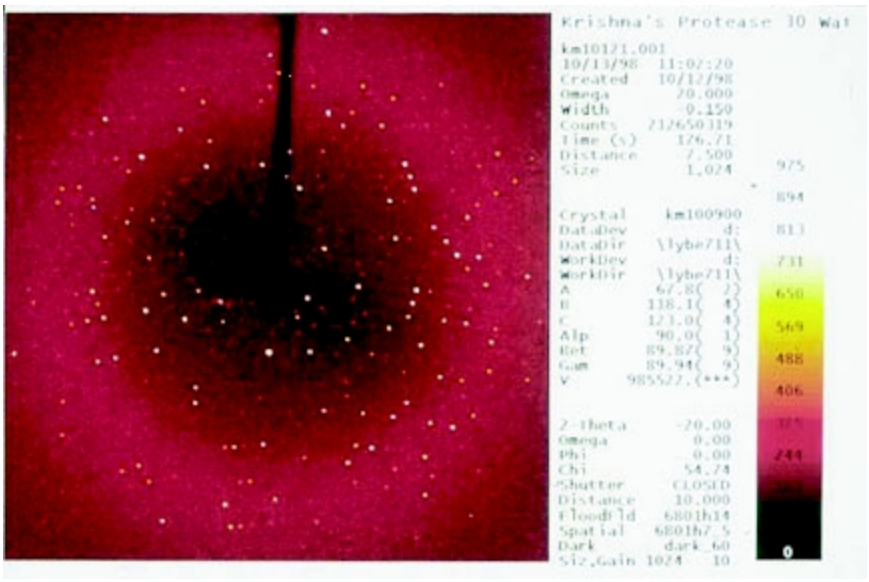


Figure 46. Diffraction pattern from the dengue virus.



Figure 47. Developmental robotic hardware for crystal growth.

between the two syringes. As soon as it does, a hair-like loop grabs it, pushes it out of the solution into a liquid nitrogen stream that freezes the crystal, and then the robot puts it in this box here, which is a nitrogen minus 180 freezer. The next step is to put it on the x-ray machine once we put in the rack. It works with

100 percent success rate, I'm sure, on Space Station, but with an 85 percent success rate in a 20-second free fall on the KC.

This is the way it's going to look (Figure 48). The little Glovebox will be there with the robot in it, and the x-ray system here. All the astronaut will have to do is put the sample in there, and he's done for the day. Our center has developed a number of drugs (Figure 49). We also take x-ray data and look at it in many ways. One way is a profile like this to prove crystals are better. People like Eddie Snell at Marshall Space Flight Center look at the mosaic spread, and it is sharper for crystals from space.

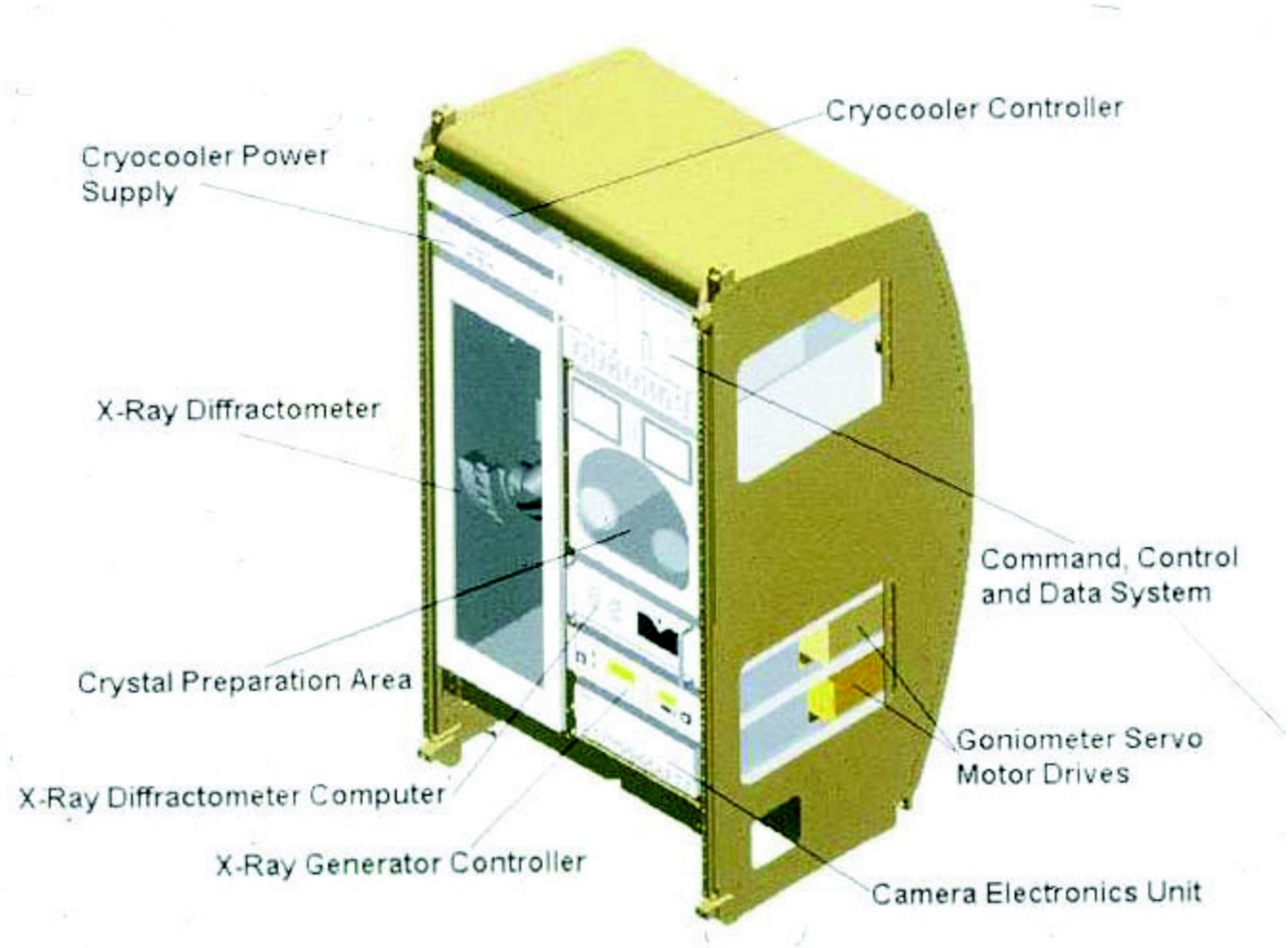


Figure 48. Robotic spaceflight hardware for crystal growth.

We are able to develop these drugs because our center has many capabilities including molecular biologists; protein purification; and a thing called combinatorial chemistry where we can actually make 1,000 new potential drugs in a week, but we make them based on the structure so they are all going to fit into an active site and block it.

Then, of course, we have 43 aerospace engineers who are very capable of making any kind of hardware. We've spun off three companies (Figure 50, Figure 51). The first one, where Charlie Bugg went, is valued at $140 million today. It has a number of drugs in clinical trials.



Figure 49. Summary of the Spacelab accomplishments of the CMC.

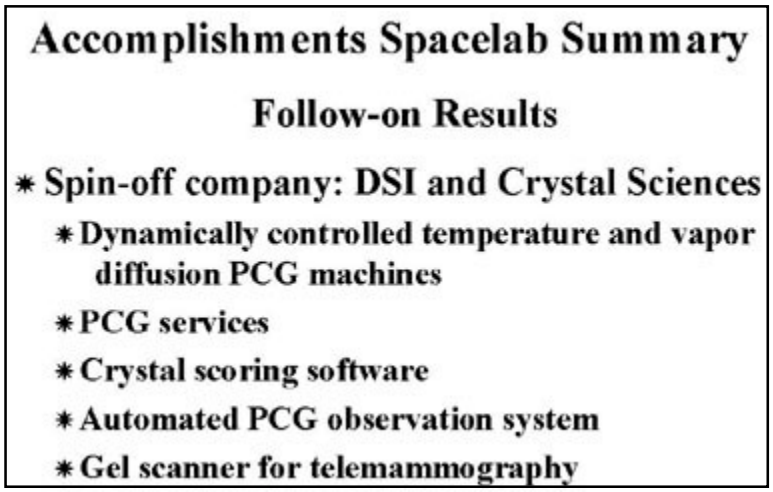


Figure 50. Spin-offs of Spacelab research by the CMC.

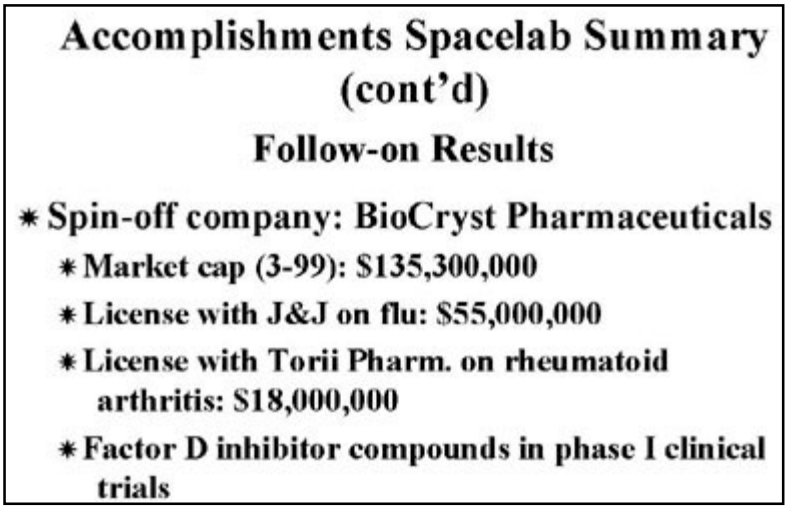


Figure 51. Spin-offs of CMC Spacelab research, continued.

Who is going to do this in space? The way you get companies involved in space is by having a program like we have on the ground, all that fancy technology that gets them excited, and space is the frosting on the cake. When we can't get a good enough crystal, we use space to help us get over that hump.

I'll quit there. Thank you.

Dr. David Larson

It has been a privilege to be involved in the microgravity research program for as long as I have. There are relatively few of us still active. Noted examples are Gus Witt and Bill Wilcox.

When we started on Skylab we had a platform that we didn't fully value. It was something that was pretty much handed to us. In retrospect, it was something that we should have cherished and made sure that it lingered for much longer than it did. The pain that it has taken to create our new platform has been excruciating and frankly, I'm very pleased that we have at least the two elements in space today. The empty cradles are the only ones that count. I'm looking forward very much to the next generation of experimentation.

Dr. DeLucas' experience reflects the intrinsic value of repeating experiments and iterating experiments. To be able to do that in real time is something that will unquestionably reward the investigators and investors for their investments of time, talent and financial resources.

I had the privilege to fly two experiments on USML-1 and USML-2, STS-50 and STS-73, respectively. The title of the effort was "Orbital Processing of High Quality Cadmium-Telluride Semiconductors." We were to look at both doped and alloyed semiconductors, but our initial choice was, because of the detector applications, an alloy, and we selected four percent zinc alloyed cadmium-telluride.

Our intent was to investigate the role of gravitational influences, both hydrostatic and buoyant convective on the crystal growth of Zinc-Cadmium Telluride (ZnCdTe). There was a good deal of prior art with regard to the influence of convection, and our system was not particularly sensitive to convection. As a result, the emphasis of this experiment was on the influence of the hydrostatic effects on the crystal growth.

We had noted in the literature, that in the region where the diameter of a crystal was changing, which is normally referred to as the shoulder of the crystal, the Russians had reported a loss of wall contact and a substantial decrease in dislocation density. Our proposal requested an opportunity to pursue those observations.

In order to do that, we put together a team. It's very important to note that team in the context here. I was at Grumman Corporation, now Northrop Grumman Corporation. My co-investigator was Iwan Alexander at the University of Alabama in Huntsville who focused on fluid flow and g-sensitivity. We had colleagues that assisted in the sample crystallographic characterization at the State University of New York at Stony Brook, Mike Dudley and several of his students, Hua Chung and Balagi Raghothamachar in particular. Then we had another part of the group at Clarkson University that contributed to the thermo-mechanical stress modeling of the process.

We were privileged on USML-1 to grow two crystals. The melt in these ampoules was unconstrained. There was no piston or whatever to simulate hydrostatic pressure. Semiconductors for the most part contract when they melt, and as a consequence we expected to have some free volume in the sample as it was growing.

By industrial standards the samples that we grew were small. They were approximately 1.5 centimeters in diameter. We opted to pursue seeded crystal growth in order to control the growth orientation. This was atypical for this particular material but common practice for other semiconductor crystals like galium arsenide and silicon. The samples that were grown on USML-2 were actually to complete the test matrix. The first one had exactly the same geometry as I previously indicated except that it had a restraining piston that simulated hydrostatic pressure. As a result, the melt was constrained to remain in contact with the ampoule wall as it grew in microgravity, just as it would be on the ground. The other ampoule was tapered. The intention was to go back to some results from very early work on Skylab done by Hannes Walter where, by controlling the interfacial angles at the triple junction, he was able to grow a crystal without wall contact. We attempted to do so by allowing the wall to fall away from this triple junction at a rate that was faster than the crystal was broadening.

The thermal profile brought the sample up almost to the melting point isothermally, then built a gradient, and then seeded the melt by moving the gradient along the axis of the seed crystal about one third of the length. The interior of the ampoule was coated with carbon to change the wetting angle. However, the wetting angles were such that the body of the liquid would move towards the seed crystal in the microgravity environment in a thermal gradient, and as a consequence we wouldn't lose contact with the seed. The seeding operation worked all four times successfully. So we apparently did that right.

The thermal profile was typical of what we used in industry to grow these crystals. As you will see, it is very important for us to grow a one-g set of crystals as a baseline. A frequent criticism of the flight program is that if you grow a poor crystal in one-g and then take the same process to microgravity and grow a better crystal, you still may not have a good crystal; you have an improvement, but you don't have a good crystal. What we wanted to compare against was the best industrial crystals that had been grown terrestrially, as well as the one-g baseline crystal grown in the flight furnace.

When we got the first two crystals back you could see a sequence of changes in the surface texture. From the seed crystal through the shoulder region and then for about a centimeter or so there was a bright surface. This was followed by a matte finish, and then a surface that mimicked the interior surface of the coated ampoule. The bright finish was indicative of an absence of wall contact, the finish that duplicated the glass wall surface had experienced total wall contact, and the matte finish region in between which separated these two regions had a fine cellular pattern due to partial contact with the wall.

As the contact angle became less and less, in the partial contact region, that is, as the liquid moved away from the wall, this cellular pattern elongated much as it would if you sliced a corrugated box structure obliquely. Ultimately wall contact was lost. About 90 degrees circumferentially exhibited total wall contact, 30 degrees on either side exhibited partial wall contact, and the rest of it appeared to be free surface. Removing the surface layer revealed that, for the length of the controlled growth prior to quench, we had grown a single crystal. That was an important improvement as many ground samples were large polycrystals with twins.

As far as the tapered growth sample was concerned, on the ground you can visualize that, because of the hydrostatic pressure, the material filled the ampoule and we grew a conical crystal. A visible cleaved interface occurred on extraction of the crystal from the ampoule and suggested that in this region we had grown a single crystal. Subsequent crystals were extracted by etching the ampoule and coating away.

There was quite a bit of controversy on taking this particular concept to space. This was our backup sample, but we were fortunate enough to have the opportunity to process it. A lot of people thought that we might lose contact with the seed. Other people made other predictions as to what the melt would look like in the region of transition, but nobody predicted what really happened, which was, in fact, that we set up a liquid bridge. Then we grew approximately 2.2 centimeters of material totally without wall contact and then an additional region with partial wall contact before we consumed our allotted processing time and quenched the sample. The creation of a pore marked where we quenched the sample. There is evidence of a liquid bridge as the sample is rotated around the cylindrical axis. There is also evidence of the contact angles. In the region of the free surface there was no evidence externally of twinning, either from the standpoint of observation using optical techniques, whether it was polarized light or regular light, or using x-ray synchrotron surface topography. We are privileged at Stony Brook to have our own synchrotron beam line at Brookhaven National Laboratory, and as a consequence we can routinely do topography, either transmission or reflection, as part of our studies. It is the norm rather than an exotic technique and indicative of the care with which these samples were evaluated. We saw in these surface regions what appeared to be a very low defect density and an absence of twins. Thus our initial input with respect to defect density in the samples that had been grown without wall contact was encouraging.

The zinc-cadmium-telluride system is an isostructural system. Depending on the application of choice, if you want to use this material as a gamma ray detector, normally about 20 percent zinc is used; if you want to use it as an infrared substrate, as was our intent, about 4 percent zinc is used. The phase diagram could be calculated. Using data from Yu and Brebrick, Don Gillies of our team at MSFC made this calculation, and in subsequent analysis of the samples, both on the ground and in flight, we confirmed that the k_0 value was very close to 1.35, as calculated for this composition.

In work at the University of Alabama in Huntsville, the calculations suggested that under our one-g test conditions and for the best estimates of our thermophysical properties, we would expect a gentle laminar flow condition, not turbulence or anything along those lines, and this flow condition should become diffusion controlled as we moved to the microgravity environment.

The longitudinal solute redistribution curve from our ground-based study suggests strongly that we are close to a diffusion controlled growth condition even on the ground since it can be fit well by diffusion-controlled theory. As a consequence, gravitationally-driven longitudinal macrosegregation was not to be the focus of our investigation. We did measure longitudinal segregation in each sample, in order to determine effective diffusion and redistribution coefficients and to confirm our calculations. In the first two flight samples we did the chemical mapping using electronmicroprobe and precision lattice parameter mapping techniques. In the second set of flight samples we used mainly photoluminescence and precision lattice parameter mapping.

If we really achieved fully diffusion controlled growth conditions and a planar interface, theory predicted that we should see no radial segregation. As a consequence, we looked carefully for radial segregation, and although our error bars were fairly large, we could not detect any radial segregation in the three types of samples, the two that were free grown and the one that was constrained in microgravity.

We were looking for radial segregation for a number of reasons. One was just to assess the quality of the diffusion controlled growth. Secondly, we knew that with a free surface there was the strong possibility of

thermocapillary flow, which is not gravitationally dependent. If it was present, we should have noted its effect in the flight samples. Even though we looked on a macro scale and on a micro scale, using the photoluminescence (PL) techniques at surfaces, around bubbles, et cetera, we did not get any response that suggested that we had a substantial flow pattern resulting from thermocapillary perturbation of our flight experiment.

The other thing that is important to document is the quality of the crystals that were grown. Optical transmission is one of the measurements used in industry that is typical for an infrared sensor. The theoretical performance of the material is 67 percent transmission. Measurements indicate that we are very, very close to that value over a very wide band of wave numbers. This was also true of the ground samples. As a consequence the strong conclusion here is that the material that we grew is very high quality, at least with respect to stoichiometry, which dominates this property.

We further substantiated this conclusion with the PL results. The full width at half maximum of the A_0X exciton peak of the flight sample was 2 eV whereas on the ground it was 3 eV; the conclusion was that both of these samples were high quality materials. It was not something that was substantially improved in microgravity; they were both good. That is an important distinction. As we move down in the energy scale, it had been reported that there were a number of peaks that were associated with structural defects. The microgravity spectra clearly shows that the peaks associated with these defects are virtually missing, and as a consequence, we drew the conclusion the material we grew in microgravity was very high quality material and very low in structural defects.

The real problem that we have with this material is that the material at its melting point is very weak, weak to the point where it may self-deform at temperature from its own weight in a one-g field. The critical resolved shear stress very close to the melting point is about 0.2 or 0.25 mega-pascals. The x-ray topograph of a ground sample shows that you have deformation coming in from the walls, and penetrating towards the interior, and that we have dislocations, and twins. The twins are the same orientation as the dislocations, as we would expect, but in the presence of the beam they are physically displaced. So we can tell discretely the difference between dislocations and twins, or micro-twins in this case, even though they are the same crystallograpphic orientation.

What should be noted here is that dislocations and twins comes from the wall towards the centerline of the material. If we take a double crystal rocking curve of this material, which measures the residual strain locally, you find is that there is a subgrain structure, and that the center of the grains are high quality typical of the peak centroid and the periphery at the boundaries is lower quality typical of the tails of the curves. You find that the deviation from the theoretical curve is primarily in the regions of the tail (subgrain boundaries).

The samples that were grown in flight with partial wall contact were mapped and modeled. The conclusion from the thermal model was that the radial gradient that they experienced was small in microgravity. We had two options with regard to the assumptions that we made in calculating the stress in these crystals. The first was that there was no stiction at the wall. The deformation would have been higher at the free surface than at the wall, but in no case was the resultant shear stress greater than the critical value. So we should not have seen deformation lines in these crystals.

If we assumed that we had stiction at the wall, you find two important changes. First of all, there is a higher stress level at the wall than at the free surface. Secondly, because of the presence of that stiction, the magnitude of the stress is much greater and in fact exceeds the values that we would anticipate being the critical resolved shear stress. So we would expect to find in these crystals deformation higher at the wall than at the free surface.

The etch pit count, or dislocation count, as a function position on the wafer, was determined using the Nakagawa etch technique. We found that there is a substantial gradient in etch pit density as we move towards the free surface side. When we took a rocking curve of the region associated with the free surface, we noted a very good fit in the tail regions, suggesting a minimum of high defect regions. Using x-ray triple axis spectroscopy, we were able to show that the circular portion of the broadening was symmetric and did not extend very far, suggesting that we had a very low dislocation density in this flight material and low strain levels arranged symmetrically.

We were able to get monochromatic transmission topographs only of the flight crystals. In the transmission topograph of a region with no wall contact, the dislocations are discrete and the dislocation count is quite low. The dislocation density in this region was 800 plus or minus 50 percent. The ground samples had a fully developed mosaic structure. From a number density, the typical order of magnitude of our ground-based material grown in the NASA furnace was an etch pit density (EPD) on the order of 10^6 to 10^5 with twinning. The best ground material that we had in our inventory was grown in the GCRC laboratories as part of a DARPA program. The EPD was on the order of 3,000. So, in fact, the microgravity material was the best that had been grown.

It is important to emphasize that the twin density in the regions of absence of wall contact was dramatically reduced. Twinning is a pervasive problem terrestrially and causes enormous losses and cost to industry. It's a process that is very little understood, but clearly it is surface nucleated. The pursuit of the origins and mechanisms of twinning in the microgravity environment is something that clearly should be done, in my opinion. I believe that it shows promise for providing information and perhaps an answer to the twinning problem terrestrially because of the enhanced containerless opportunities and the potential to control and perturb the interface, triple junction and bulk geometries.

Based on the above discussion, we can draw the following conclusions from this pair of experiments.

First of all, it's our contention that we did in fact grow these crystals under a diffusion controlled growth environment.

Secondly, the material that we grew in microgravity qualifies as ideally perfect material in terms of x-ray dynamic diffraction. This is not a common thing to encounter. It suggests very low strain material. The greatly reduced lattice strain was such that we were able to get monochromatic synchrotron transmission topographs of this material, and it is the only ZnCdTe material in which we were able to do so.

Lastly, and I believe it is critically important from a numerical standpoint, is that our typical ground samples had a defect distribution with a full mosaic structure and twinning, on the order of 10^6 to 10^5 etch pit density. Typical commercial products had an EPD of 50,000 to 100,000 and the best terrestrially, was on

the order of 3,000 EPD. The material that we grew in microgravity, in the regions where we had no contact around the periphery of the sample, was on the order of 800 ± 400 EPD.

Thank you.

Dr. Matthew Koss

One of the pleasures of being here these two days has been to listen to the previous talks. When the distinguished writer and historian David McCullough spoke at Rensselaer Polytechnic Institute (RPI) a few months ago, he made a point of stressing how important it is to understand history, because to not understand your own history is to be rude by not paying the proper debt to those who came before. I particularly appreciated the discussions on the early Spacelab program. Five or six years before Marty Glicksman had even performed the basic ground-based research at the Naval Research Lab in which the conclusion was that you need microgravity to answer the next question, the facility that his experiment eventually used was already being created. That was a marvelous story to hear and see.

Right now I would like to talk a little about the Isothermal Dendritic Growth Experiment (IDGE). On the assumption that most of the people here are not materials scientists, I'd like to start at a basic level.

If you were to look at a piece of freshly solidified metal or alloy with a magnifying glass, you would see that the surface is not particularly uniform but is made up of all these different grains. If you could look even more closely at the individual grains with a powerful microscope, you would see an even finer structure. That grain structure and the finer structure that makes up the grains are due to what we call dendrites, and in many cases, this determines the properties that are important to how a metal or an alloy works or functions.

A material doesn't take this shape or form this microstructure pattern in an instant. When you form a solid material from a melt, when the material solidifies, the pattern emerges as a moving interface leaves behind the wake of solid where essentially the physical, chemical and electrical properties come from. It's important to understand this process if we are to have any hope of controlling it, or in controlling the products of solidification.

Dendrites occur most commonly in alloys, but they are really quite ubiquitous in nature. They occur in salt solutions. They also occur in certain organic materials (Figure 1). On the right is a picture of organic material that takes on the shape of a dendrite. If this were a motion picture, that solid would be moving forward, the side branches would be growing, and eventually the solid would fill all the space available. Cognizant of my role to recognize the history of this program, I'd like to go back to the history of dendrites, as far back as Johannes Kepler. Kepler was the first to speak about dendrites, and he was talking about the most common dendrite that we know, which is the snowflake. I know there were seven inches of dendrites here just the other day.

One of the most interesting things about Kepler's thinking about dendrites is that it's the first written example of the question of morphogenesis, or where patterns, or complex patterns come from. He was trying to find a scientific answer to that question, not a theological one. That is the first milestone in the history of dendritic growth.

The first modern mathematical theories started perhaps 50 years ago when there was a full understanding of calculus and differential equations, atoms were fully understood, and great progress was made. Unfor-

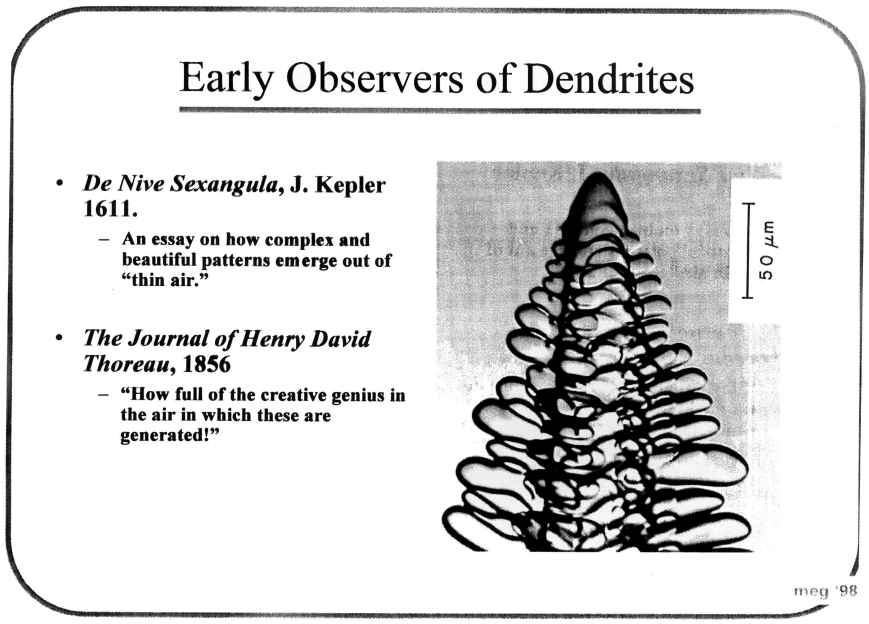


Figure 1. Early observers of dendrites.

tunately, or fortunately for the research we've done recently, a full solution to the dendrite problem did not emerge. The task was to produce a fully predictive model that would explain how fast that solidification front advanced, and what size scale features became evident.

The dendrite problem, as I said before, is important primarily to metal and alloy industries, but it has also become a model problem in the physics of pattern formation. Because it grows under non-equilibrium conditions, it's a model problem in non-equilibrium physics. And because the full solution to it is perhaps going to be a numerical simulation, it has also become a model problem in computational condensed matter materials physics. Thus it has an old history and it is an important archetypal problem today.

The current theory was well developed even before the flight experiments described here provided wonderful confirmation of key elements, and made many additional contributions to our knowledge. The first and the most important feature of dendritic growth is that heat transfer is vital to the process. As you can imagine, if you take a small piece of a solid and immerse it in a fluid that is colder than its melting temperature, the fluid will want to freeze, it's just looking for some instructions on how. The liquid will begin to freeze at the interface of the piece that is already solid, and as it does so, it will release heat. Understanding how the heat flows away from the growing interface is the number one problem.

It was well understood even when that first heat transfer solution was formulated 50 years ago that you are looking to find two things. You are looking to find how fast the solid forms, and you are looking to find a size scale, i.e., how big are the characteristic features of the forming solid. Those are two unknowns, and one only has a single equation, the heat transfer equation. So there cannot be a complete solution without a second element. One needs to find some other physics, a second equation, so the two equations can be solved for the two unknowns.

The second bit of physics that emerged to couple with heat transfer was the physics of the interface. Over the years both the basic heat transfer theory and the basic physics of the interface made advances and modifications, and their coupling was likewise modified, but a fully predictive model that could be adequately tested did not emerge.

The problem, which we recognize now, is that the heat transfer element of the problem is thoroughly corrupted by convective heat transfer. You need to remove convection from the problem. If you look at what the theory predicts and what experiments on Earth predict, you don't know whether the basic coupling of these physics is incorrect, or whether they are absolutely correct and you just can't add gravity and convective heat transfer properly. That was why a flight experiment was necessary. In some sense, this provides a model for the elements of a successful flight experiment.

The scientific objectives were very clear on why one needs microgravity. The requirement of microgravity was unique. Other attempts were made to get around the coupling problem but they were unsuccessful. Microgravity was the only way to take the next step in understanding the fundamental problem of dendritic growth. The results of a flight experiment were anticipated to be significant. In other words, it wasn't going to just answer one question, but the answers were expected to be of use to other researchers, the field would become more robust, and eventually this would yield practical applications. The expected time frame was certainly longer than the six months quoted for a flight experiment to have a particular commercial aspect. This was and is fundamental research. However, Al Sacco showed earlier that even the commercial research that is taking place today had its roots in what he described as basic fundamental research from 25 years ago.

All these issues were addressed together and proved through a rigorous peer review process. Having to prepare for a rigorous peer review process improved the eventual scientific output. Now, the microgravity data has begun to close the gap between what was needed to be known and what was known.

I'm going to speak about this one figure in some detail (Figure 2). We are plotting a parameter from the heat transfer theory, the Peclét number. Thus, this graph is a test of heat transfer theory. The open symbols represent measurements in terrestrial conditions of the Peclét number. The dotted line is a first-principle theoretical prediction or calculation. There are no adjustable parameters in that line, no fudge factors. That line is the basis of a zero parameter test of theory. There is a big difference between terrestrial data and theory, and no way of determining how much of that difference is due to gravity and how much is due to a poor description or an incorrect model of the dendritic growth process.

The closed symbols are the microgravity data of the Peclét number. You can see right away at a glance that the microgravity data is both very different from the terrestrial data and is in fairly good agreement with the zero parameter test line. In other words, the fundamental physics of heat transfer as described for the dendrite is a fairly good predictive model. However, if we look more carefully at the data, we can examine three small areas in which further explanation is needed.

The first is at the lower supercoolings. Supercooling, on the bottom scale, is the measure of how far below the freezing point the melt is. At the low supercooling, the data lifts up a little as compared to the trends at the larger supercoolings. Based on the overall success of the model, we have good reason to believe that this is explained by a modification to that model that includes the effect of a cold wall close to the growing

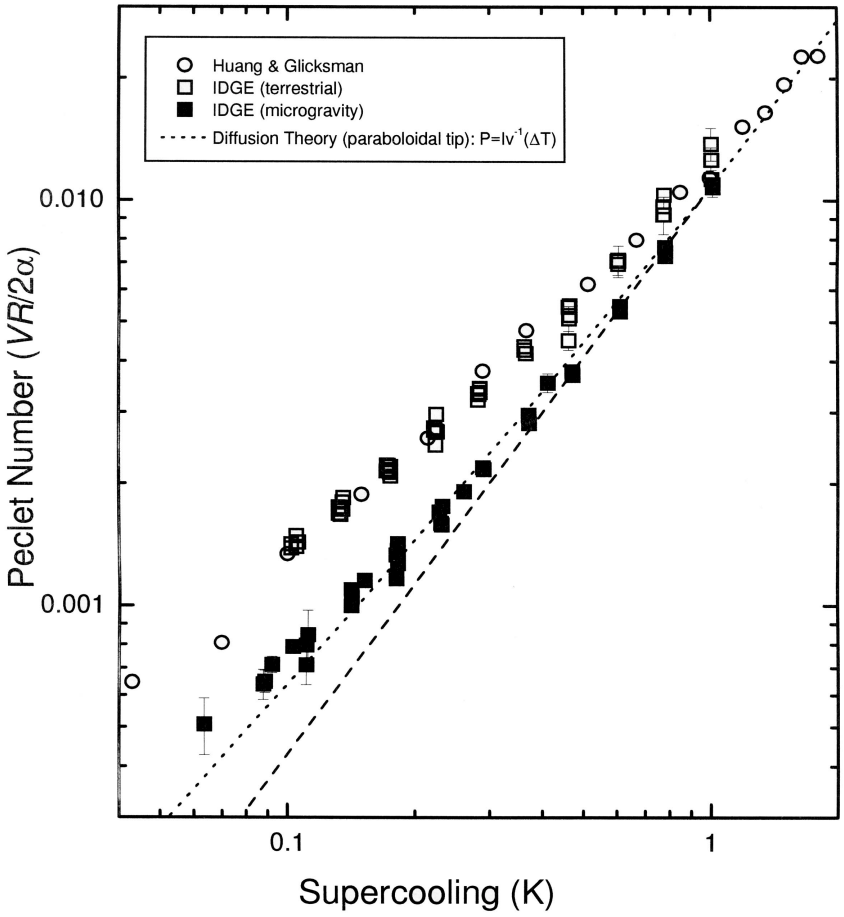


Figure 2. A test of heat transfer theory.

surface. So we are satisfied we understand what is going on. In the higher supercooling area, although it's a very good match to the theory, the data is a tiny bit too low, and this difference is not due to measurement uncertainties. It's real!

At first we thought that this was due to small variations in the shape of the dendrite at the tip. We did some calculations and we saw that that was not true. I think the thesis work of a member of our group, Jeff LaCombe, made a very good case that this slight lowering of the data compared to theory is due to the side branches that occur in dendrites. The side branches aren't included in the model described by the dotted line, but side branches or real dendrites throw out a little extra heat, and that extra heat slows down the dendrite, slows down the heat transfer process, and produces that slight lowering.

We also think that the side branches explain the extreme scatter in the data. That scatter is also not measurement uncertainty. The error bars on those data points are smaller than the data points symbols. Thus, when there is a 20 or 25 percent spread in the data, it's physical, it's real. The parameter we are measuring has that much variation.

Just like snowflakes, no two snowflakes are the same, no two dendrites are the same. Their side branch structures are slightly different, and that contributes to a slightly different heat transfer problem. On this

last point, it's plausible and I think it's good speculation, but it is not yet proven. It's one of the things we are working on.

An overall message from this plot is that there was a long and well established theory, and what turns out to be a pretty good theory, that couldn't be tested without the microgravity data. When microgravity data was available, it not only validated the theory in large part, but in small part, it showed what are the key corrections to the theory. So now at least on the heat transfer component there is a very good explanation of dendritic growth that people are comfortable with and that they can use in further modeling.

As I said before, the dendrite problem has two main features. One is heat transfer and one is the selection principle. The selection principle is still very much an open question. We have some data from the flight that doesn't resolve it and more work is needed.

To give some sense of what I think the issue is, I have this quote from Philip Anderson (Figure 3).

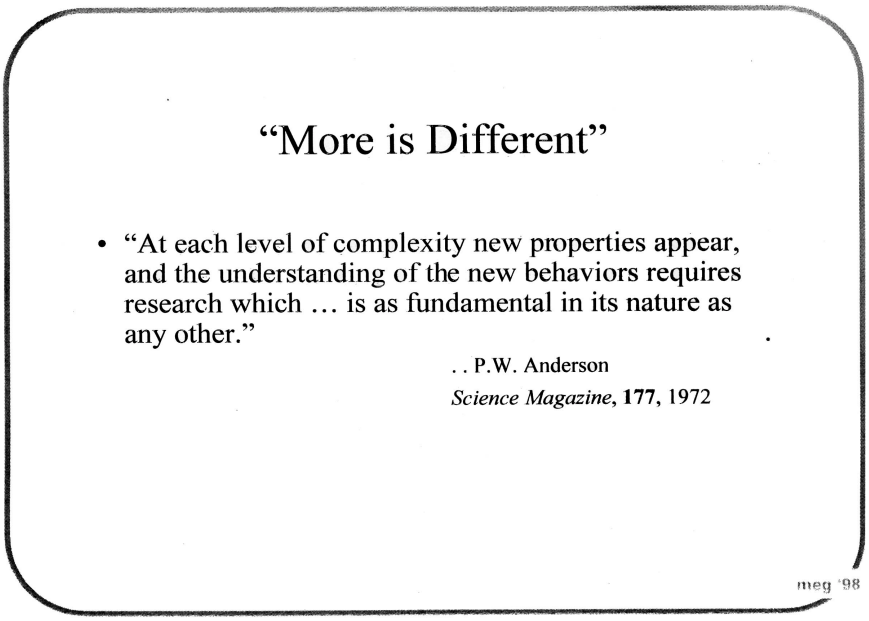


Figure 3. Quoted from *Science Magazine*, Philip Anderson, 1972.

Dendrites are complex structures. We can't predict what emerges as important by looking at the basic physics of the dendrite, which is well understood. The only way to understand the problem is to appreciate the complexity, measure the complexity, and try to identify what is the fundamental physics that is important. We are planning to do that and hope others will be doing that in their further work too. There is still more work to be done on selection.

Personally, I think our greatest measure of success on the flight is that others are using our data (Figure 4). These two pictures are from other research groups that are doing dendritic growth studies and have started to use the data and results of our space flight. The first picture is from the University of Illinois, Urbana Champaign, where a group is doing phase field models of dendritic structures. They are generating dendrites on a computer with a particular set of equations and then going back and looking at the shape and other metrics of what they obtain and comparing it to our microgravity data.

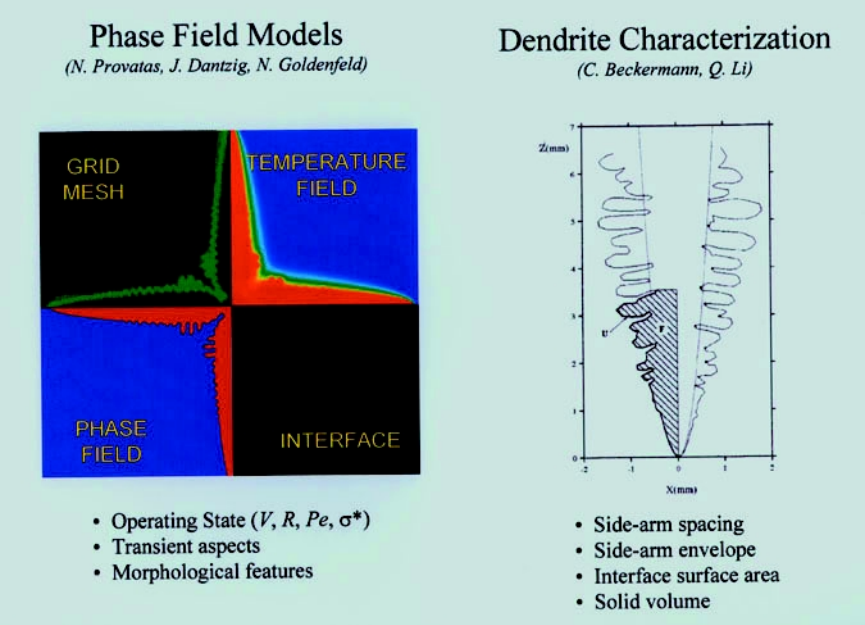


Figure 4. Crossover uses of data from spaceflight.

At the same time, a group at the University of Iowa is making further measurements on other parameters from our data set. They are using our data set from the NASA archives and some of our information and doing further measurements. There are other groups that are doing similar things. Sam Coriell, who is here today, and colleagues at NIST and Carnegie Mellon are doing some theoretical calculations of a modification to the basic model. They've just recently had an important result, but they don't yet have a pretty graphic that I can include on a figure. If they can do that, I can make a more comprehensive figure that shows what others are doing.

Perhaps dendritic growth is at a stage now where quantum electronics was 50 years ago. There are some basic principles that are understood and there are some interesting effects that are seen. But it's going to take a combined and concerted effort of many people to push understanding forward enough to create a robust industry like we now have in electronics, and hope one day to have in industry, such as the manufacturing of structural engineering materials from castings. The process has started. There are some fundamental results and the modeling goes on.

The last thing I'd like to say is some important lessons have been learned. Many of the experiments that have been discussed today have talked about telescience. In most cases they were talking about scientists on the ground interacting with their counterpart, the payload specialist on-orbit. Our experiment wasn't like that.

Those of you who know Marty Glicksman know that this is a very good representation of our experiment (Figure 5). Marty is on the ground with the help of Jeff and the other members of the team, including me. We are remotely interacting with our experiment. Our experiment can run autonomously, but any interaction is by computer only.

There are some subtle points about telescience that are hard to make. Telescience certainly allows the scientist on Earth to be the astronaut in space. But when I say telescience, I mean more than just remote

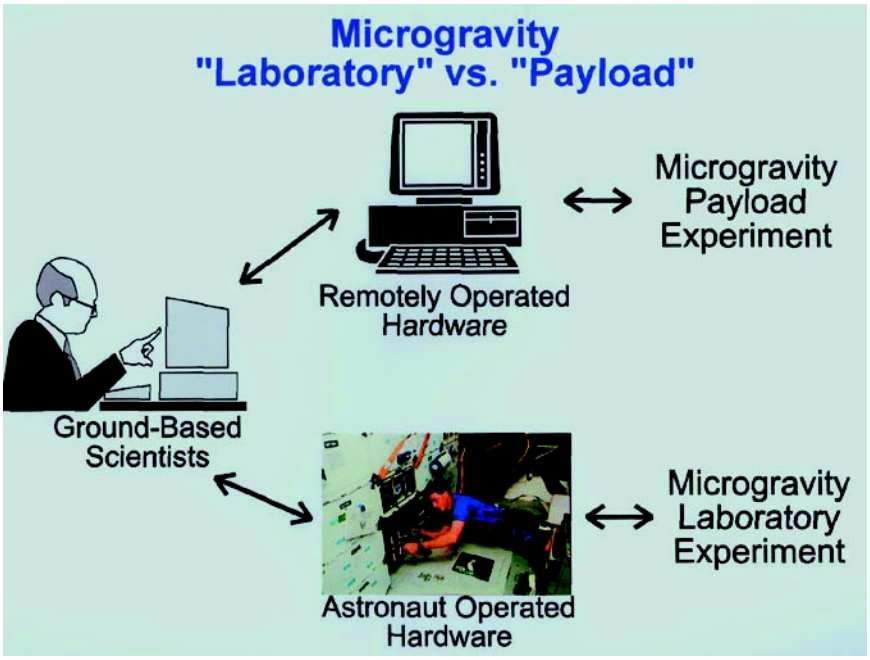


Figure 5. Laboratory versus payload in a microgravity experiment.

control. NASA has been doing remote control for many years. Telescience is more than just remotely changing the parameters of an experiment.

Telescience is more than just changing the experiment because something has happened with the operations. We take advantage of opportunities. There may be more time to do an experiment, or we have to make changes because of a hardware malfunction. To be sure, that's a proper use of telescience, but it's more than that. Telescience is pushing to understand what nature is doing, looking at the early results, seeing something that was unexpected, and changing what you do and doing different things to better understand something that you didn't even know was a possibility before you started the experiment.

Re-flights are crucial for further exploration of an emerging issue because the bulk of our data analysis takes place months after the flight is over. But, some of that information is available before the flight is over and some is available and building as the flight goes on. Telescience means looking carefully at every bit of new data and seeing if there is something different that you could do or checking if nature has told you something that you didn't know before, and you should now immediately explore further.

The other major point about telescience is that you don't only have to be at the POCC (Figure 6). We did telescience and communicated with the POCC while staying at RPI. This had tremendous advantages to us in that we did better quality work since we didn't have to select in advance everything that we needed from our own laboratory and our libraries and move it to Huntsville for three weeks. At the same time, it allowed us to involve 40 RPI students in assisting us in this experiment. There has been some discussion about where is the next generation of scientists who are working on microgravity experiments. Well, possibly they come from the experiments that are going on now, and if we can include 40 or 50 students at a top engineering school in microgravity research, we are spreading the word. In addition, when you do remote telescience, you also do remote education and remote community involvement.

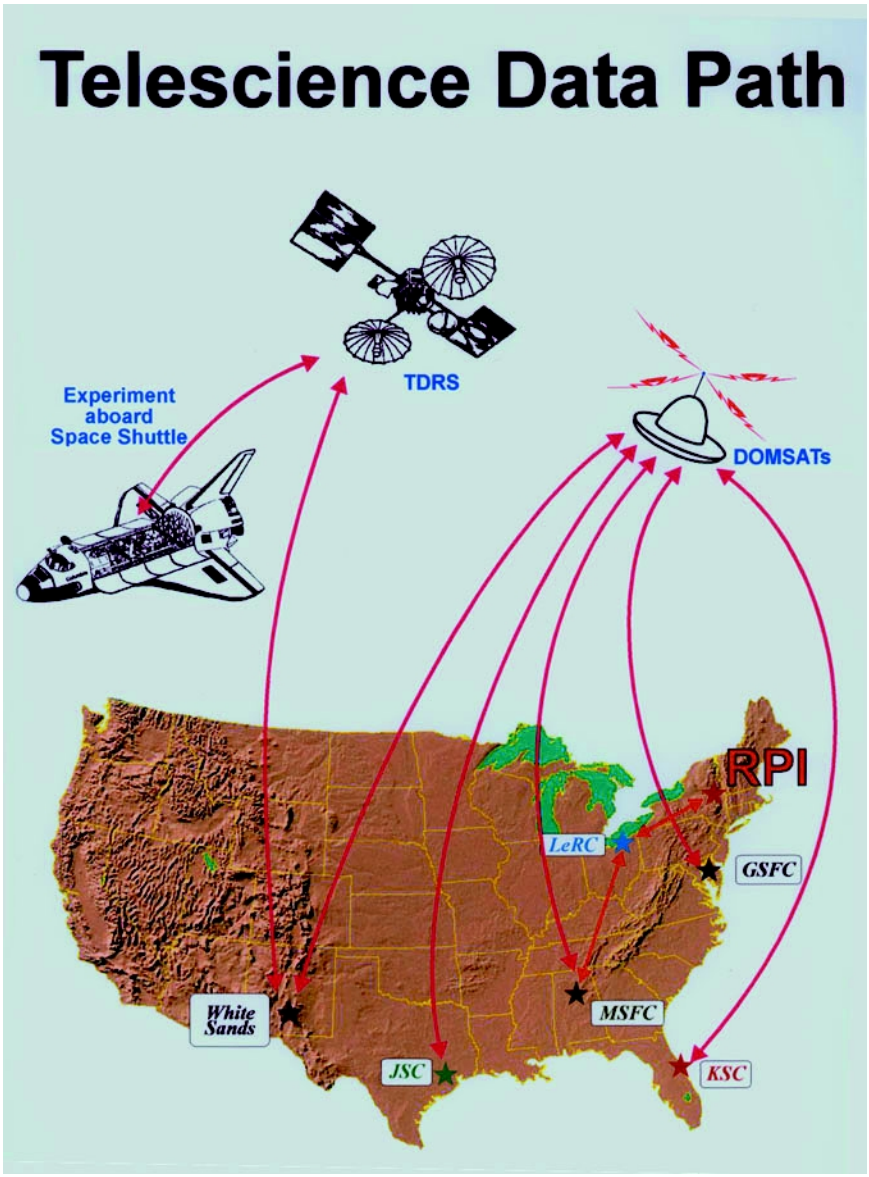


Figure 6. The telescience data path.

All this talk about telescience brings up the second important lesson that we learned from the IDGE, and that is that operations are as crucial to scientific success as hardware development. We depended on our operations people. Sherwood Anderson, the mission manager from the USMP series is here today, and we depended on Woody and the cadre at the POCC to help make our telescience a reality, to implement what we thought we needed, even if it wasn't what we expected and practiced in simulations, and they did that.

The IDGE team at RPI was one component of a larger team. We had a NASA engineering team that built this hardware and made it work and interacted with us to understand what we were trying to do as scientists.

NASA is not just a funding agency, they become a partner. The IDGE is an RPI-NASA experiment, and if it's successful, that's where the credit goes, and if it's not successful, that gets shared equally too. In our case we were successful. We worked hard and on occasion we had some luck, and luck counts. We appreciate both.

It has been my pleasure to speak to you today.

Dr. Simon Ostrach

This is a special occasion for me because I think this is the first scientific meeting at which my son and I are both participants. It was a source of comfort too, because I knew being the last speaker of the day, there would at least be one person who would have to sit and listen to me.

I was one of the pioneer workers on buoyancy driven flows, and when I come to microgravity meetings and hear all of the terrible things, that buoyancy corrupts and buoyancy overwhelms, it is a little uncomfortable. Nonetheless it is a pleasure to come here and see so many old friends. To use Henny Youngman's line, I guess it's a pleasure for me to be anywhere at my age.

Brad [Carpenter] referred to the fact that I started 55 years ago at what was called the Aircraft Engine Research Laboratory of NACA. I think I am the only active person from that generation left. Al Sacco said, you know, you have not changed at all. How come? I tell you, doing microgravity research keeps you young, because it took 17 years for me to get to fly and my experiment got to be known as "fly before I die." Before I get into telling you what we did in our experiment, I obviously have a warehouse full of war stories. We have heard some really wonderful ones, and I'm going to try to keep mine to a minimum.

But I want to say this. I came back in 1968 from a trip to the Soviet Union, and a guy by the name of John Caruthers called me and said, you know, we think buoyancy is causing all kinds of grief in crystal growing, and we have been reading a lot of your stuff. So would you get involved? I did not know what a crystal was or anything of that sort. Later on during the Skylab program, Owen Garriot and some of the crew were pretty bored, and I think people like Bob Naumann and others were sending up cute little experiments for them to try with grape juice and wrench handles. By this time John Caruthers had moved on to be the director of the division at headquarters. There was a lot of pressure on John to use all this film and to analyze it and see if it had scientific merit. He then asked if I would put together a team of materials people and fluids people, because John already was an enlightened materials person who realized that what happens in the fluid state determines the solid state of matter.

So I had the courage — I do not know how — of saying, "Okay, John, if you want me to get some really top people, you have got to let us go to a nice place." So I asked to go to Sanibel Island and we rented a condo. Marty Glicksman headed a team of three materials people, and I brought down three fluids people. The idea was we would work in the morning, play in the afternoon, and work in the evening.

Well, the putting together of people from those two disciplines was a most unique thing. We went through cases of beer and boxes of pizza and never left the place except for a couple of hours. We could have well been anyplace. But it brought together two communities who saw that mutual interaction made sense. This started NASA's funding of multidisciplinary research. There was no other major source of that support in this country. If none of these research results that you have heard here today never occurred, I think that was a major contribution of the microgravity research program.

Gravity primarily influences the fluid phase of matter. In the 1960s there were some enlightened people at NASA. They brought together a group of panels under a program whose acronym was PACE, which is

Physics and Chemistry Experiments. They put together one group on bubbles and drops and they put one together on fluid and transport phenomena. They asked us, "What do you think would be different in space?"

One of the things that came up was that surface tension would be very different (Figure 1). The next question I asked myself was, would surface tension generate any flows? If you realize that surface tension depends on temperature, concentration and electric potential, then a gradient of any one of these along the free surface ought to be able to do something.

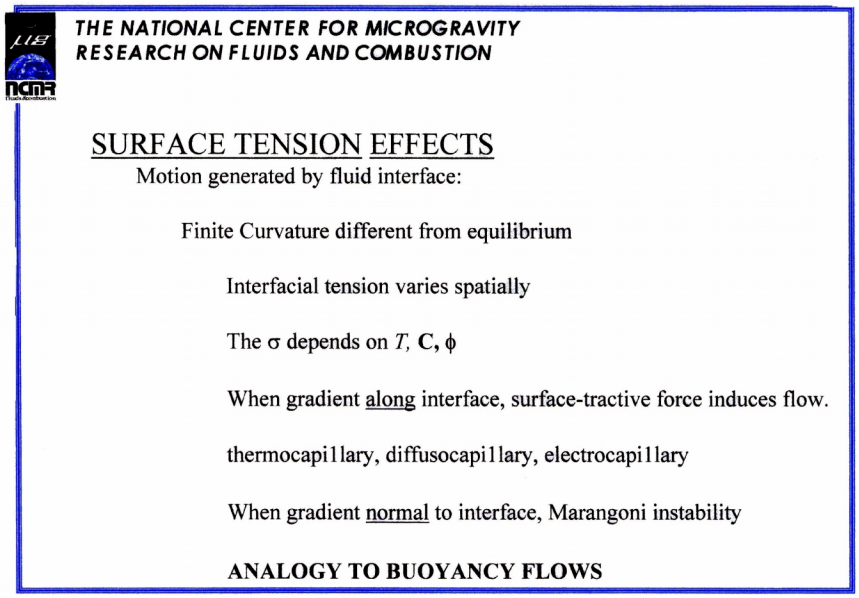


Figure 1. Surface tension effects.

There had been a great deal of study of cases where the gradient was normal to the interface, primarily because it was a simple experiment to see. A Frenchman by the name of Benard heated some whale fat on a hot plate and he noticed a beautiful honeycomb structure. This mode is known as the Marangoni Instability. Lord Rayleigh's brother-in-law, on a cold day, observed that same kind of honeycomb structure on the top surface of a tub of soapy water that they used in the pubs to wash the glasses, and went home and told Lord Rayleigh, and Lord Rayleigh did some very elegant analyses to describe the situation. So this was a subject that had been studied extensively.

If the gradients of temperature or concentration are along the free surface, the flows are different from the Marangoni instability and are called, respectively, thermocapillary or diffusocapillary flows. There had been two attempts to study such flows, simple analyses, one by Levich and one by Gus Yih and they both had very serious mathematical/physical errors in the analysis. Also, there are two similar modes of flow in buoyancy driven flows. If the gradient is normal to gravity, you immediately get a flow; if the gradient is opposed to gravity, you have what is called the Rayleigh instability. So I was kind of intrigued and thought we should study such flows. Then some 70 reviews and grief, we finally got accepted to do an experiment. Then the Challenger accident came along. So it was really 17 years from the start when we were approved to do this research to when the experiment was flown. But there was a great deal of groundwork that needed to be done.

Just to give you a little bit of a clue on the mechanism here, surface tension driven flow, which is what we were trying to study, is driven by temperature induced surface tension variations along a liquid-gas interface (Figure 2). It's important in many engineering applications; the containerless processing of materials, which was thought to be one of the great technical breakthroughs possible on the Spacelab; welding processes. There are lots of other things. But again, I get very crabby when the press asks me what the application is, because for fluid and thermal scientists, this microgravity environment is the same as a high magnetic field laboratory or ultra high vacuum facility or cryogenic facility is to a physicist. Since I see the whole world as a fluid, whether it is cars traveling down the highway or money moving to the banks, I get a little resentful when I now have a new world in which to examine the subject of my interest and everybody wants to know right away why it is important, what it is going to do for the taxpayer. But it is going to do a lot. Naturally.

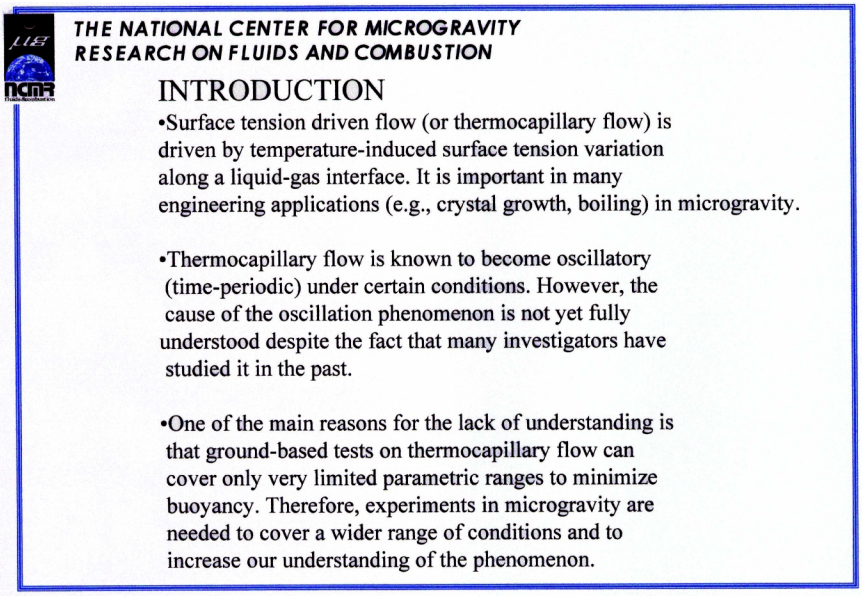


Figure 2. Introduction.

To observe thermocapillary flows on Earth is very difficult. To see any surface tension effects you have to go to very small capillary tubes or very thin paint layers, because if you impose thermal gradients, obviously in a gravitational environment buoyancy flows will dominate.

A couple of materials scientists started to examine such flows in liquid bridges, to simulate the floating zone process of growing crystals. They noticed that under some conditions the flows became oscillatory. Well, if you say oscillatory to a fluid dynamicist, he immediately says, instability, whatever that means. But there are some elegant mathematics that you can do if you say it's an instability. So everybody assumed this was instability, and I must say I wasn't any different. We started to do more careful experiments of the same type and we found we could not correlate the data; if this were an instability, there would be a critical Marangoni number to describe it.

I missed one of my war stories. I have a very dear friend of mine whom I knew back in the old aeronautics days by the name of Luigi Napolitano. He invited me to his lovely villa in Naples, and for three weeks I told him all about capillarity and thermocapillarity. Of course he was delighted when he heard that the parameter associated with it was called the Marangoni number, for an Italian physicist, right? We would

take occasional trips over to Capri where he had a villa. Luigi then took on the cudgel to become the fluid dynamicist for the European Space Agency, but he would not make the distinction between the two modes and that distinction is not merely a pedantic one. The physics is different as are lots of other things. So he set the European Community back by about 15 years by calling all these flows Marangoni flows. Anyhow, this Marangoni number was not sufficient to correlate the data. That's almost a real story, incidentally.

The oscillatory mechanism was a real question. We had enough evidence, we thought, that indicated it wasn't an instability, and we posited a physical model and took on the whole world in trying to prove it. But the fact of the matter was that we could not really determine what the cause of these oscillations was because the range of experiments on Earth were limited. At best, to observe these thermocapillary flows you had to have experimental apparatus on the order of millimeters, and even under those conditions the buoyancy effects were about the same order of magnitude. It was very limited. That was one of the reasons for going to space as well.

This is the logo (Figure 3). It's conceptually a very simple experiment. We are going to heat a dish of oil. I decided that we would do the experiments in cylindrical containers because it gave us much more flexibility in imposing the thermal signature that would drive the flow, much easier to make measurements and observations than these liquid bridges, and to make identical measurements on Earth and in space. So it's basically a dish of oil that is heated by some means or other.



Figure 3. Surface-tension driven convection experiment.

Again I want to reemphasize what Matt Koss said. We could never ever have done this experiment, designed the equipment, test it, integrate it, develop the diagnostics as it was done at the Lewis Research Center. No way. I'm hearing more and more that scientists should do these in their universities. I'm not even sure that at the Mecca — MIT? — they could do it. But they certainly couldn't do it at my university. I could never have done this experiment, had such state-of-the-art complex apparatus work, and work properly. The Lewis Research Center was a full partner.

We hear a lot about people in space. We're going to Mars and the moon and all of that. You never hear that we need humans in space to do interactive laboratory science. That's what the fluid and thermal sciences are all about. They are interactive laboratory sciences. Things happen on a scale of minutes to hours. They are complex. You have to have interaction. We were fortunate that Gene Trinh was the principal fluids payload specialist. It was incredible to me that we had to go through all kinds of hoops to get payload specialists on USML-1, the first mission devoted to American science. We were fortunate on USML-2 to have Fred Leslie be the primary payload specialist. The secondary payload specialist, Al Sacco, helped on our experiment some, and so did Bonnie Dunbar. But crew interaction was crucial to this thing, and all these experiments were run that way. Again, I want to point out that there are several equal partners to the PIs, the field centers who can make PI-specific complex equipment work; the crew who help you run it.

Let me briefly tell you what we did and give you a few of the spectacular pictures. These experiments were to study surface tension driven convection. We really wanted to describe the developing flow, the time developing flow, and the steady-state flow under a variety of conditions, a variety of ways of imposing the thermal signature. We wanted to get some handles on this oscillation business. The first series of experiments, denoted as STDCE-1, were done aboard the USML-1 mission in 1992 (Figure 4). Although we exceeded the critical Marangoni number, that the ground-based research indicated as being the value above

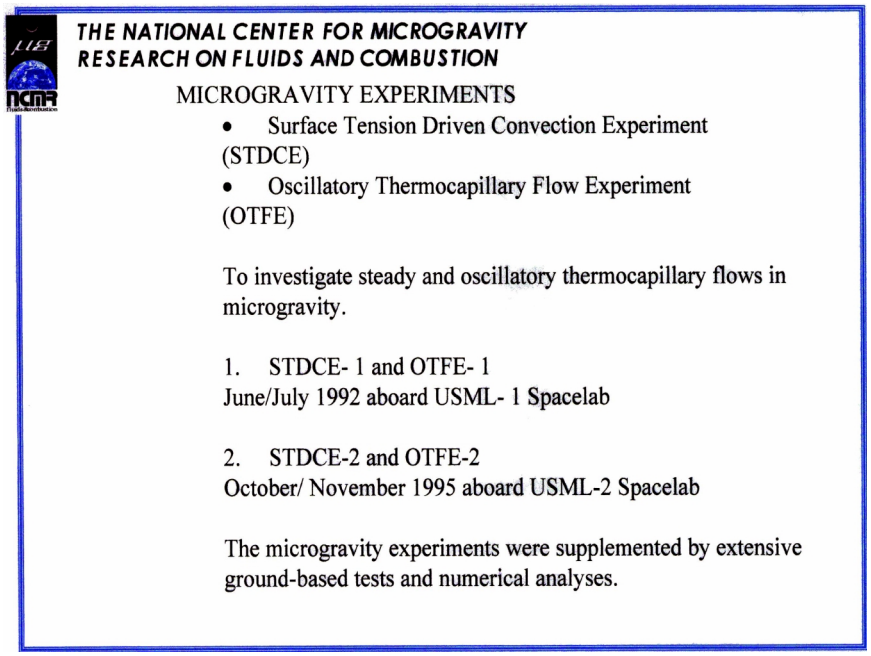


Figure 4. Microgravity experiments.

which oscillations would occur, we observed no oscillations over an extensive range of the associated parameters. We used the Glovebox facility to extend the parametric range even further. We redesigned the experiment for the flight aboard USML-2 in 1995. Of course these were supplemented by a great many ground-based numerical analyses, and KC-135 flights were very helpful in defining many elements of the experiment. Incidentally, I didn't give enough acknowledgement to Yasu Kamotani, who is my co-PI. His experimental skills and perseverance were major factors in the success of the experiments. I guess I made this point before. This is interactive laboratory science. That is one of the main reasons, in my judgment, that we need humans in space, and that is why I've been a big fan of the Space Station. These tests were run interactively. The team followed STDCE through a video and downlink. The data obtained in one test, was

transmitted by telescience to our graduate students who could do a lot of calculations and tell us the next test parameters.

Again, the jump from USML-1 to USML-2 in telecommunications was unbelievable (Figure 5). On USML-1 we had tape recorders and we were always competing with the other PIs to use the tape recorder. We had the High Pack system in the second series where we got three state-of-the-art diagnostics measurements down immediately, in real time, and we could work with that. Of course then we ended up with 200 hours of data to analyze.

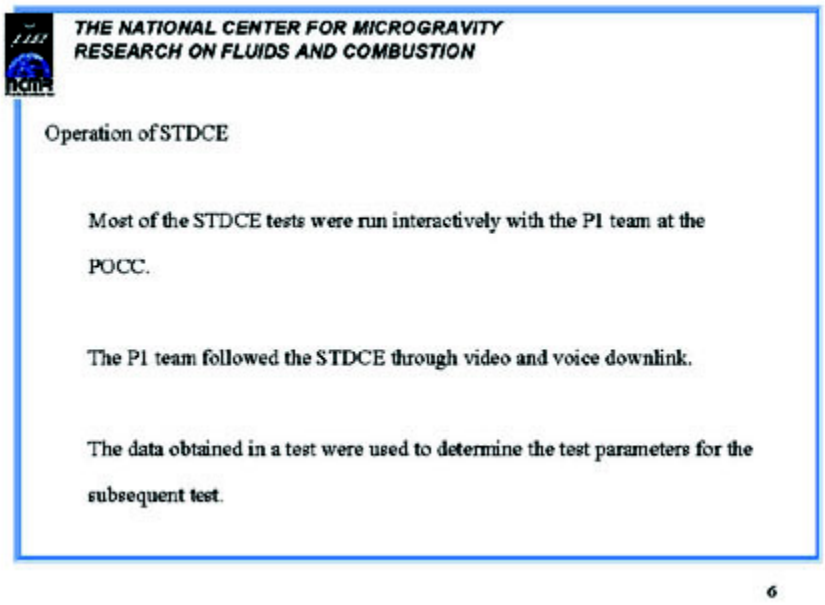


Figure 5. Operation of STDCE.

As I said, we went to cylindrical containers (Figure 6). This is a configuration that had not been studied before. It had many advantages. We went to silicon oils because their thermophysical properties and in particular, surface tension were well know. Also they do not contaminate. We decided that we would use different heating modes, different ways of imposing the signature. We did it either by an internal cartridge heater that would stick up in the middle of the cylinder, or we could retract it and use external heating by a CO_2 laser. Through an optic system we could then broaden the beam or intensify the beam and get a whole distribution of different types of thermal signatures. Can you imagine going up on the Spacelab with a CO_2 laser, which is an invisible laser? That gave a lot of heartburn, but we worked it. The other interesting thing is on Earth the hydrostatic pressure keeps the free surface flat, but in space, if you pin the ends, change the volume, you can get all kinds of curved surfaces. Since the flow is driven tangentially along the free surface, we wondered whether that would cause the internal flows to be different, and in fact they were.

The three diagnostic tools we used were flow visualization with tracer particles, thermography for free surface temperature measurements, and in the second series of tests in USML-2, a Ronchi system, which is a modified interferometer system for measuring the surface deformation. In our model of what we thought was the cause of the oscillations, we said surface deformation played a dominant role. As a matter of fact, people were beginning to observe the deformations. So we used this Ronchi system to measure it well.

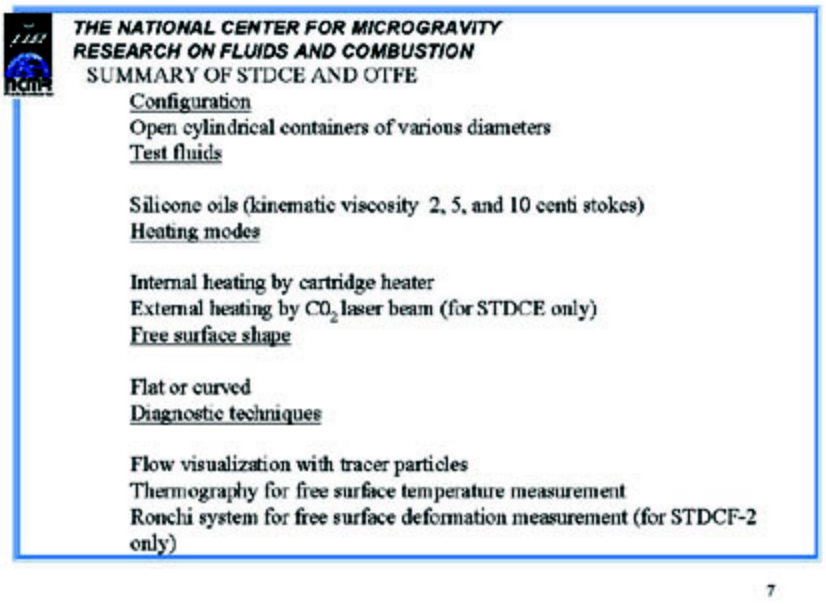


Figure 6. Summary of STDCE and OTFE.

Depicted here is the cylindrical configuration with the two heated modes (Figure 7). On Earth if temperature gradient were imposed, by either mode, buoyancy flows would be generated. At the same time, since surface tension usually varies inversely with temperature, the surface would be pulled like a belt from the hotter region to the colder one. The question is would this influence the flow below the interface and how? On Earth in fact, the primary action was confined to maybe the upper third. The rest of it became thermally stratified. You can see again that the minute you add a horizontal temperature gradient, you also had buoyancy corrupting the flow. Anyhow, that's the problem. If you got up into space, of course we would remove that corruption and see what would happen. In fact the flows were very different.

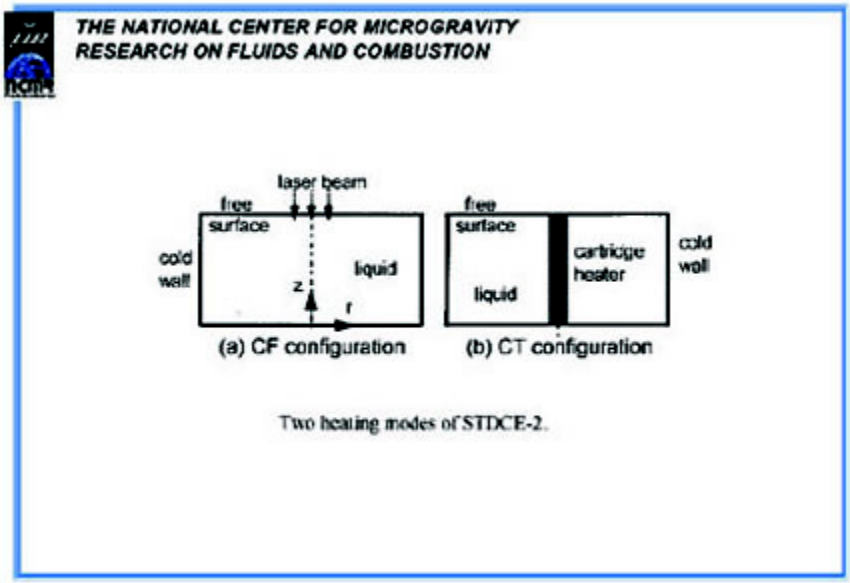


Figure 7. Two heating modes of STDCE-2.

This is a schematic of the hardware of the system (Figure 8). These are the test cylinders.

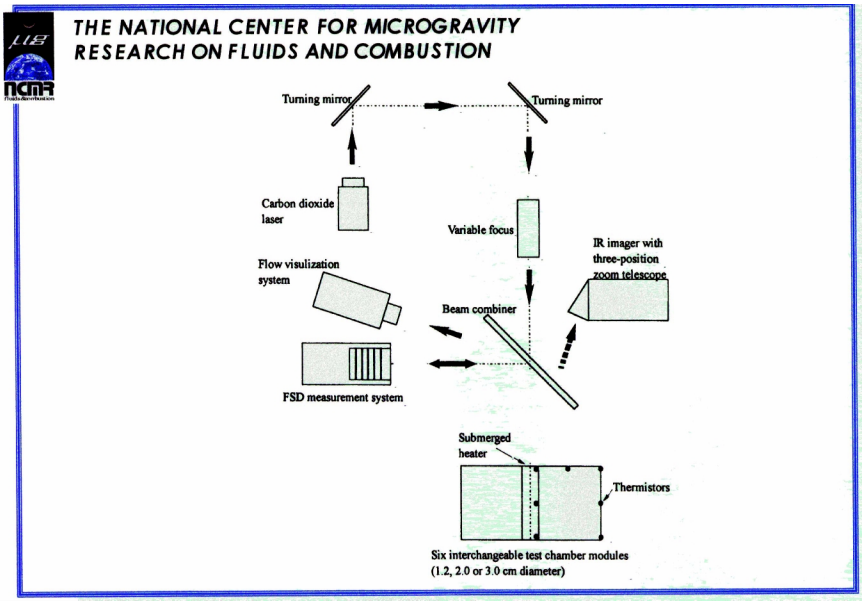


Figure 8. STDCE hardware schematic.

Here is the carbon dioxide laser going through the optic system. So we could make any sort of spot we wanted. If we turned that off, we could bring the heater up into this position. Imposing the laser heat was what we call the constant heat flux tests. With the rod heater we obtained the constant temperature difference tests because the walls were all cooled by water.

You can see the flow visualization CCD camera; this was the IR imager; and this was the Ronchi system. It was pretty complex using state-of-the-art stuff.

Let me quickly summarize the results (Figure 9). In STDCE-1 it was a ten centimeter diameter cylinder with ten centistoke oil. We designed this to have Marangoni numbers an order of magnitude greater than

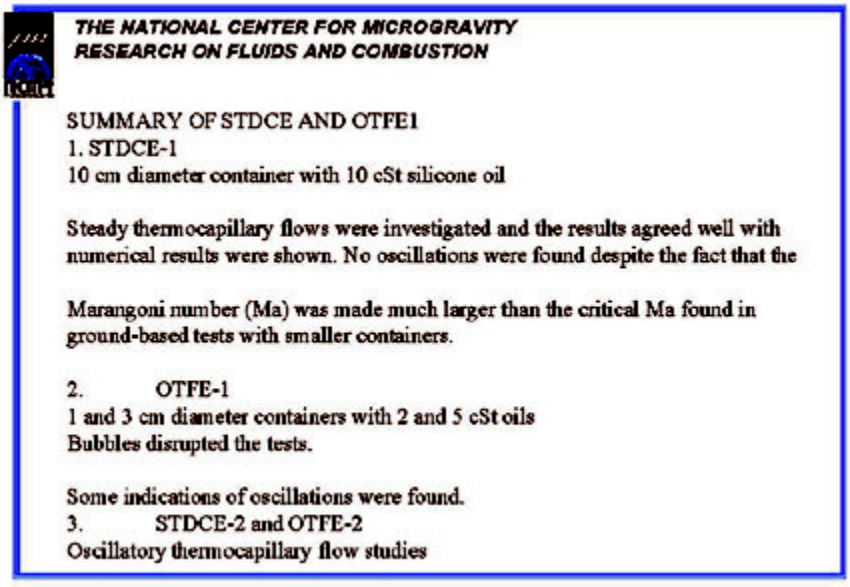


Figure 9. Summary of STDCE and OTFE-1.

what was quoted as being the critical Marangoni number for oscillations. We didn't find any oscillations but we were able to really find all the effects of different thermal signatures, different surface shapes, and things like that. In OTFE, we got corrupted by bubbles. We thought they came from the JPL experiments, but we found out that epoxy, no matter how careful you deal with it, does trap air which gets out. From these tests we got an indication that oscillations would happen in this range, but we couldn't get any quantitative data. So these OTFE really served as the basis for the design of the Spacelab-2 results.

Our flow is very different, penetrating the entire cylinder, whereas in one G, due to the stratification effects and buoyancy, it only moves in about the upper third. This has some other interesting implications. We did have a thermogram of the free surface. There was software in the system so we could get temperature distributions. From these we were able to get quantitative velocity, temperature distributions, reproducible, as accurate as you would ever want, over a broad range of conditions. This was not a golly gee whiz, look at how funny or different this is. This is quantitative reproducible scientific data.

In Figure 10 you see something you could never do on Earth (Figure 10). This is the curved surface configuration. In fact multiple cells were generated by this curvature. A lot of interesting differences were caused by the free surface curvature, which I don't have the time to go into.

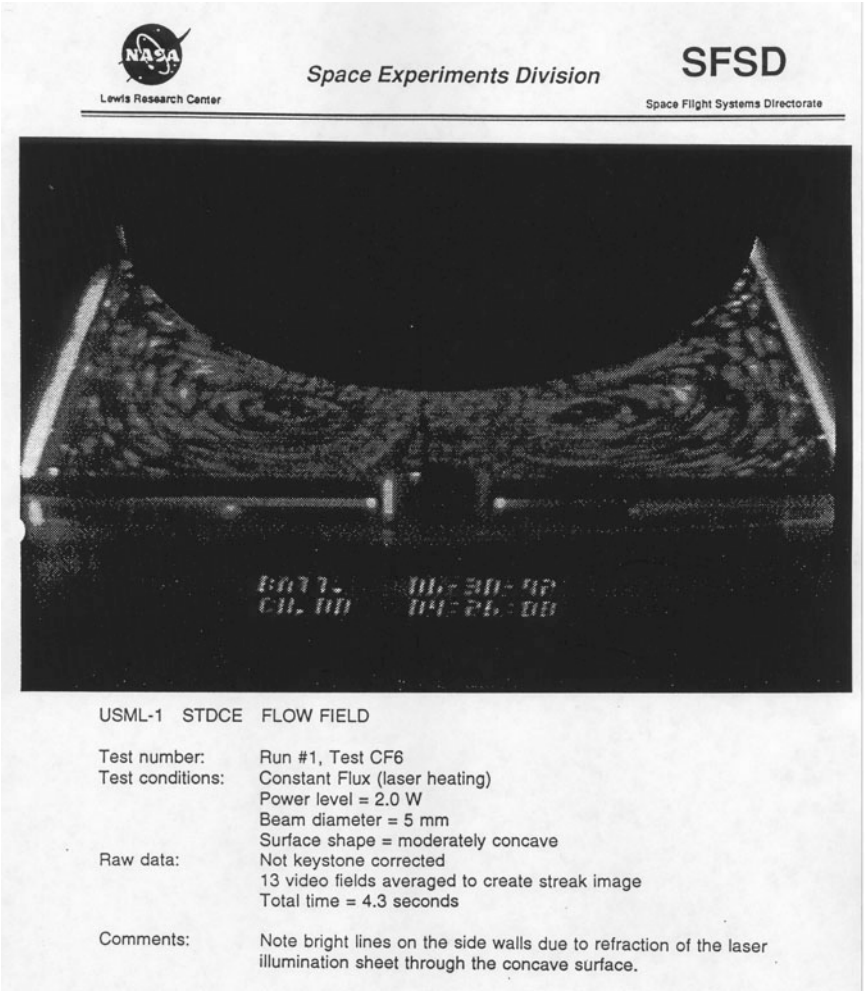


Figure 10. USML-1 STDCE flow field.

Now we get to the USML-2 experiments (Figure 11). There is primarily the same cast of characters. The only difference was that Fred Leslie was now the fluids payload specialist who did a great job for us. The main objectives of this were to determine the onset conditions and the nature of the thermal capillary flows (Figure 12). Again, also to study the effects of the heating mode and the free surface shape on the oscillations. We wanted to see if this physical model that we posed, a coupling among the velocity field, surface temperature distribution, free surface deformation, was valid. At any rate, we wanted to find if the free surface deformation played an important part in the oscillation mechanism.

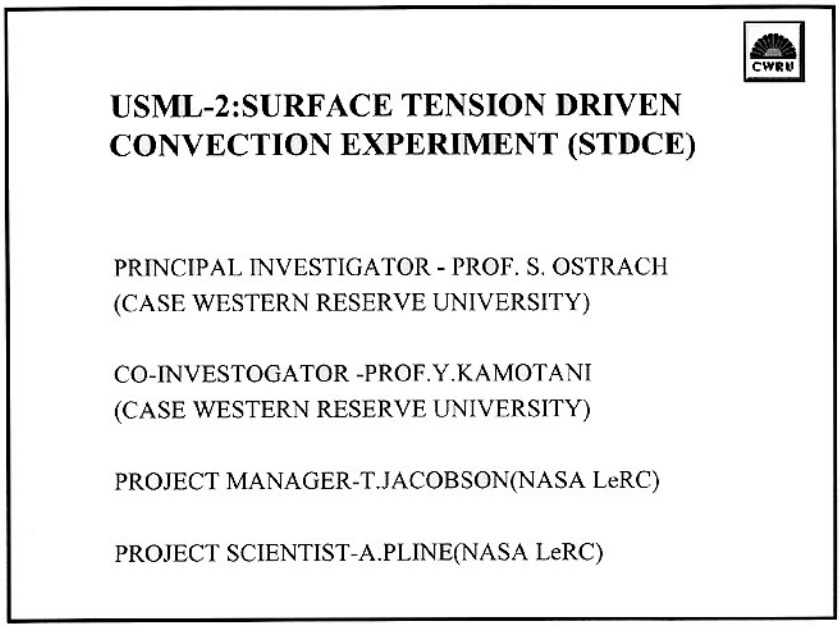


Figure 11. USML-2 STDCE personnel.

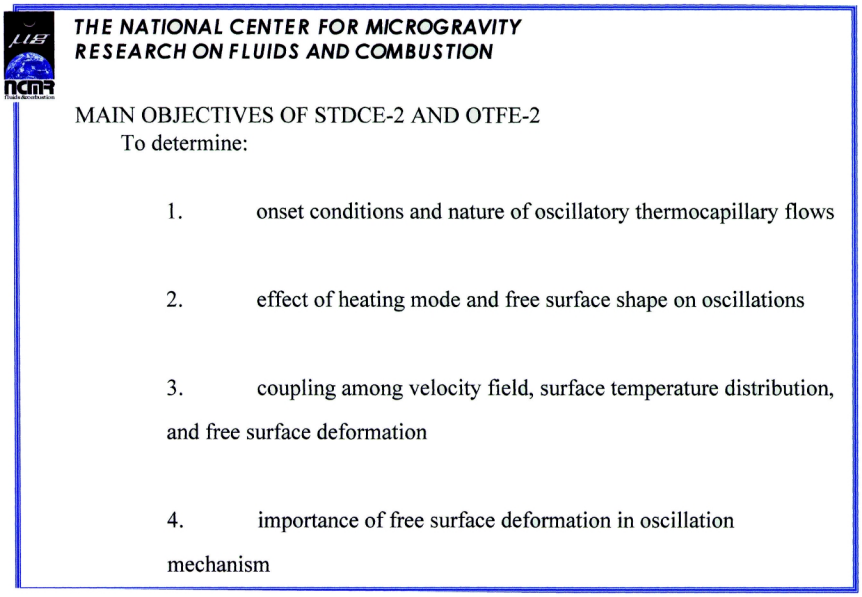


Figure 12. Main objectives of STDCE-2 and OTFE-2.

Basically, the containers here were smaller and the fluids were thinner so we could get higher velocities (Figure 13). I want you to note that the cylinder diameters are 1.2, 2 and 3 centimeters. If you determine

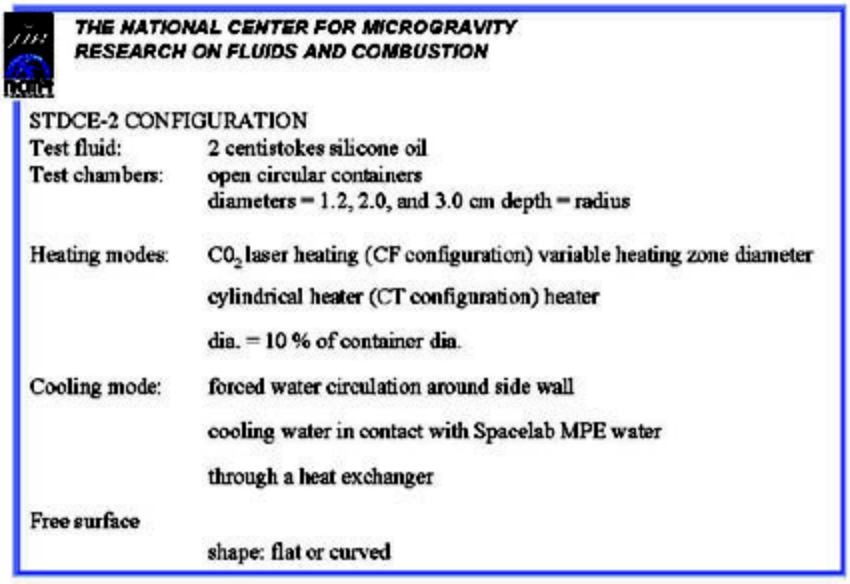


Figure 13. STDCE-2 configuration.

the dynamic Bond number, the ratio of buoyancy to thermal capillarity, even under best conditions, that's the smallest diameter here, it was about unity on Earth, which indicated the buoyancy effects were about equal.

Some of the critics of our dynamic model were saying, well, you know, it's buoyancy that is affecting it. So we took exactly this cylinder which we tested on Earth and we took it up into space. This was the largest one on Earth where it wasn't overwhelmed by buoyancy. We had results absolutely identical in space and Earth, which indicated that buoyancy didn't play a major role. Again, we varied all relevant parameters over a broad range.

Let me show you some of the very interesting patterns (Figure 14). When it started to oscillate, it would start as a two-lobe rotating pattern. I used to say that this was like a phonograph record, but I realized that dated me. So I guess it's like a — well, CD-ROMs don't rotate, do they? Anyhow, you get the picture. This is the 1.2 centimeter constant temperature configuration. These are the exact cylinders that we tested on Earth. They rotated much more easily in space. In other words, a much lower DT, which was com-

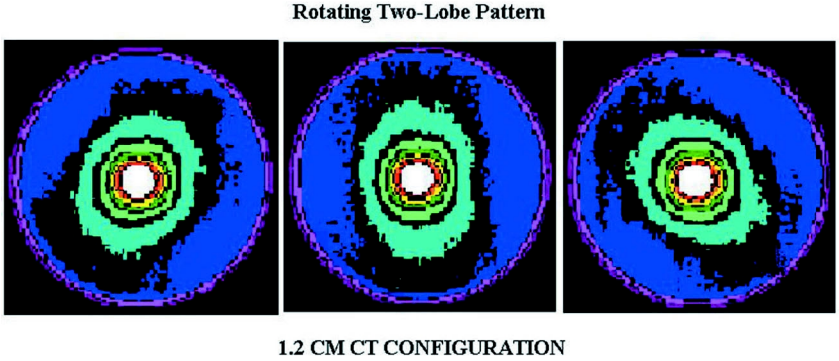


Figure 14. Rotating 2-lobe pattern, 1.2 cm CT configuration.

pletely consistent with our concept that the free surface plays a role in it. As we increased beyond the critical, we went from a rotating to a pulsating pattern (Figure 15). Now instead of rotating it would just flip back and forth like that.

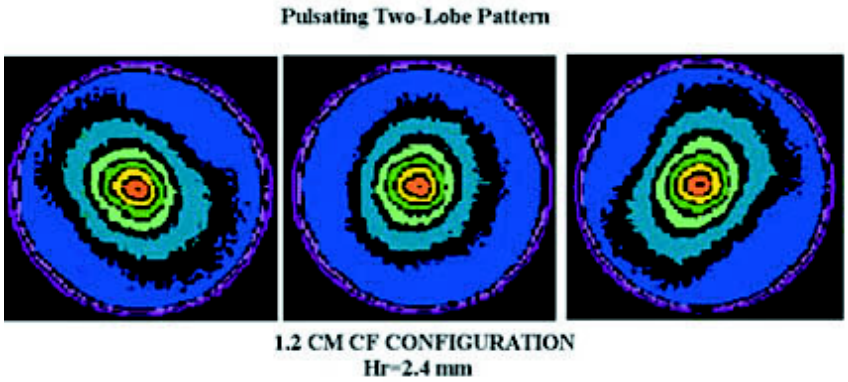


Figure 15. Pulsating 2-lobe pattern, 1.2 cm CF configuration.

For the equivalent laser beam, to the rod, a tenth the radius of the total cylinder. You get very much the same as for the DT tests (Figure 16).

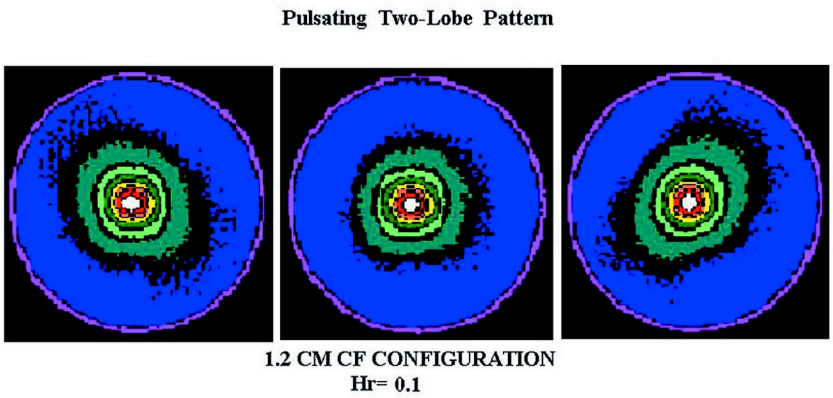


Figure 16. Pulsating 2-lobe pattern, 1.2 cm CF configuration.

You notice that these are all two-lobe patterns. We went to a little bit larger cylinder, the 2 centimeter cylinder. Incidentally, these rotations come on rather subtly, but we had three different diagnostic tools and the imposed flight time on the data. And it is amazing how well we could correlate the onset of the oscillations. Once we got them to oscillate, we would then continue to increase the temperature differences. Here is a 2 centimeter CT when it starts to oscillate (Figure 17). This becomes now a rotating three-lobe pattern.

Don’t ask me why, but some of these questions still need to be addressed.

If we go to the 3 centimeter, which was the largest diameter cylinder that we tested, we again start out with a two-lobe pattern and beyond it, and we come up with a three lobe pattern (Figure 18).

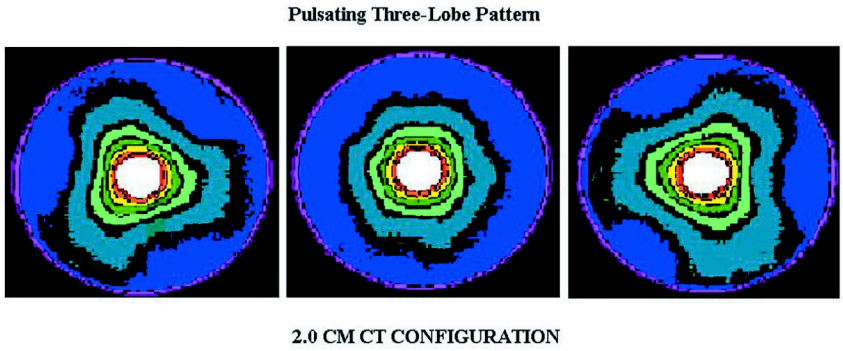


Figure 17. Pulsating 3-lobe pattern, 2.0 cm CT configuration.

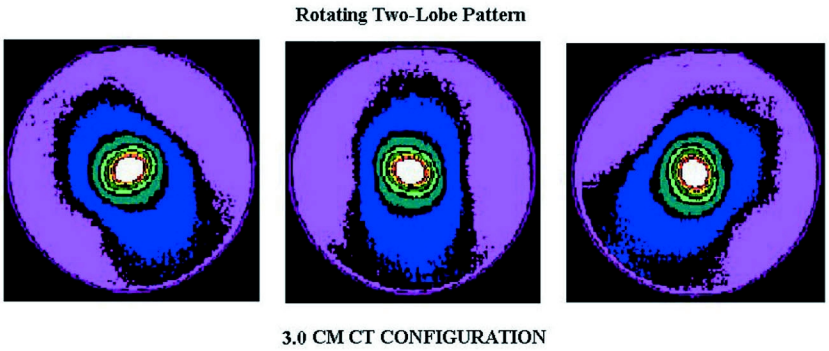


Figure 18. Rotating 2-lobe pattern, 3.0 cm CT configuration.

When you start going to the larger containers, it goes from two-lobe to three-lobe patterns (Figure 19). Let me just give you a feeling for the concomitant surface deformation. This is sort of the Ronchigram (Figure 20). It's a sketch of the Ronchigram. You can see where the temperature is highest there is a low in the surface deformation; where it is coldest, there are highs. In fact, you see that these Ronchigrams show you the free surface doing about the same thing, only out of phase with the thermograms. We then correlated all of these conditions with a modified capillary number, which is indicative of the surface deformation. We seem to have at least satisfied ourselves that this three-way coupling is the proper mechanism for the oscillations, which is very unusual. It's the most complex fluid physics phenomenon that I have observed in 50 years.

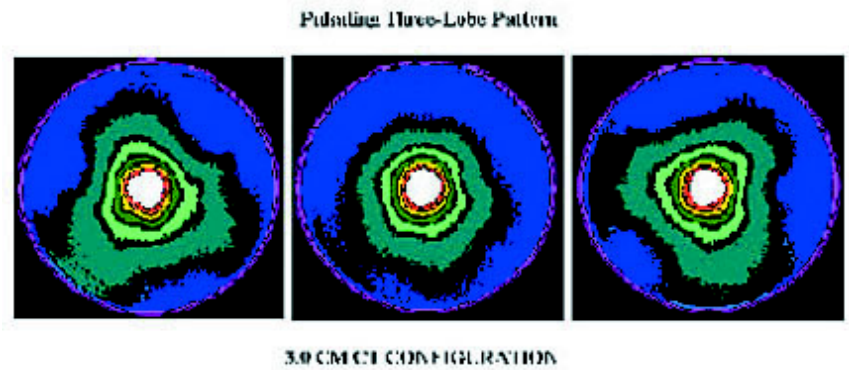


Figure 19. Pulsating 3-lobe pattern, 3.0 cm CT configuration.

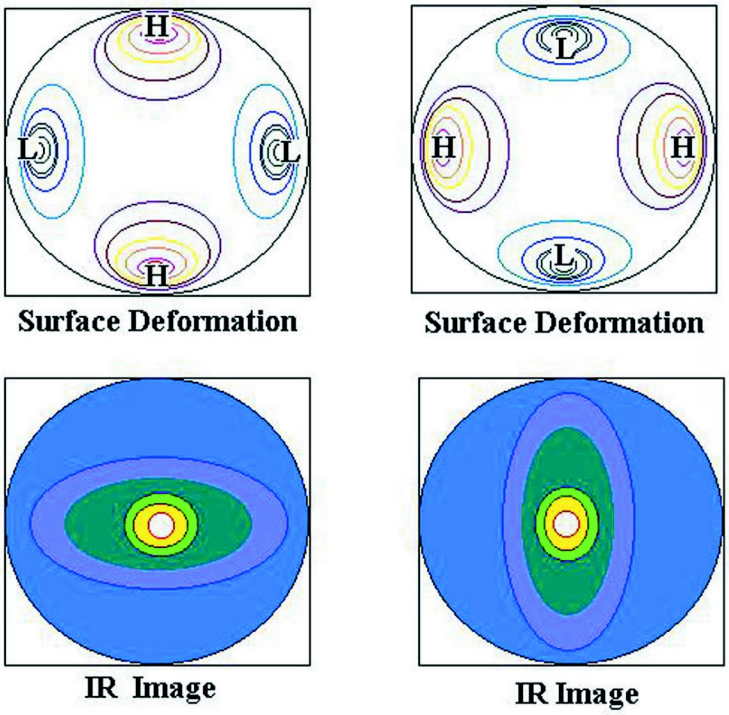


Figure 20. Comparison of surface deformation and thermal information.

What is the importance of this? Well, a lot of firsts (Figure 21). It was the first quantitative thermocapillary flow experiment. Also, I think it was the largest open free surface in a space environment. Again, we were all worried early on about what G-jitter was going to do. Is that going to knock our oil out? The best scientific data was that Bonnie Dunbar said she had never seen any effects of G-jitter. When I found out two weeks before the flight that the orbiter was flying in a catcher's mitt mode and there would be vernier rockets fired every second, I almost had a heart attack. But in fact it didn't affect our results, particularly

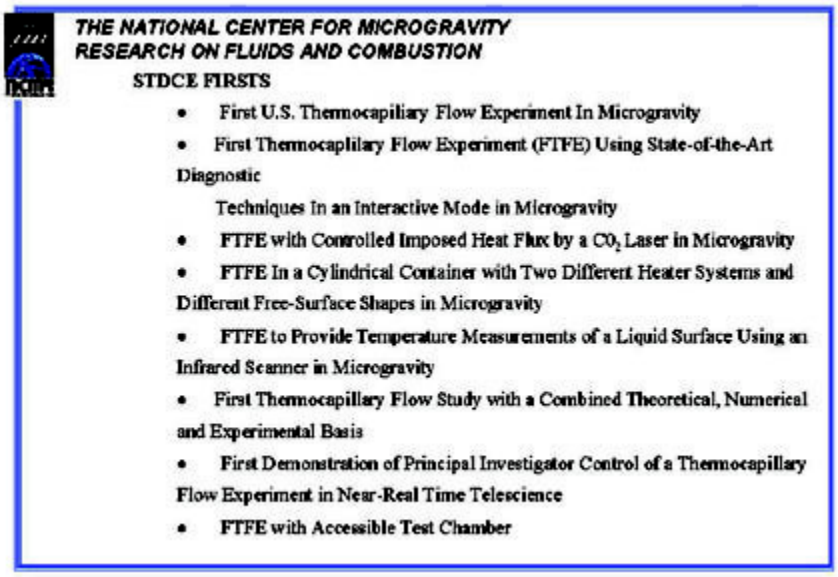


Figure 21. STDCE firsts.

when we were thinking of oscillations. Despite all of that, those finite disturbances and everything, we never got oscillations at Marangoni numbers an order of magnitude greater than the so-called critical. So it was the first thermocapillary flow using state-of-the-art diagnostic techniques in an interactive mode. It was the first one using the CO_2 laser. It was a lot of other firsts. It was one of the first fully quantitative laboratory sciences experiments.

Let me just say one other word about the rest of the program. Since my Center is called Fluids and Combustion, I was getting some veiled threats from the combustion community to say something about that field.

This next slide emphasizes another major contribution of the microgravity research program (Figure 22). This is what the whole program consists of. You see it has all of these various topics.

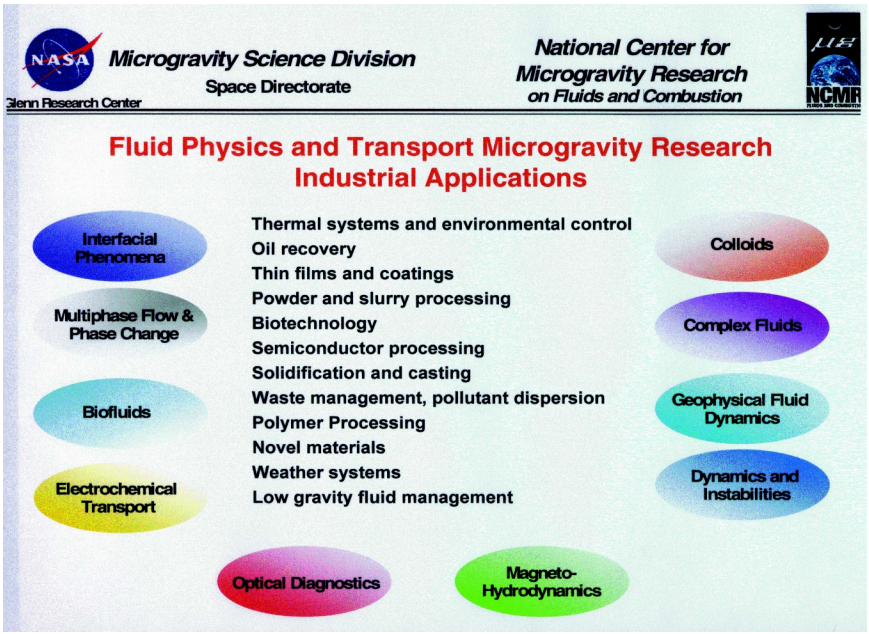


Figure 22. Industrial applications for fluid physics and transport research.

Fluid mechanics has always been thought of as dealing with water and air, but in fact real fluids that appear industrially and otherwise have gunk and goo and particles and phase changes and electricity and chemistry happening. Clearly these kind of messy fluids would be different in a low gravitational environment. I think it is an enormous contribution that the program has in fact anticipated the renaissance in fluid mechanics, going to real fluid mechanics, to look at real fluids. I think Ronnie Probstein in a talk that he gave at my Center said that we know less about micro- and meso-scale effects on macroscopic phenomenon than we knew about turbulence at the turn of the century.

This is an enormous contribution. Again, I think this has industrial applications. We are testing this out very, very soon. We have 12 corporate VPs from both aerospace and non-aerospace industries coming to our Center, and we are saying we want to transmit this knowledge to you, see if any of it is of value to industry.

I think there was an omission in not having someone describe some of the really neat combustion stuff. You just add a little chemistry to fluid mechanics and you get combustion.

Gerry Faeth says something about how buoyancy is just an ugly thing that gets in the way of combustion. There are equally unusual phenomenon that have been discovered through the combustion research program. Flame spread and flammability. Things that you think are not flammable on Earth and will not be flammable in space turn out to be more flammable. A lot of counterintuitive things. Soot formation and things of that sort.

The other thing that blows me away is that all of us are really impressed with the tremendous advances in computers and computer power. Since establishing this Center and finding out the diagnostics that have been developed I am amazed. We now can see reality so much better than we ever could and measure things to nano units. Some of the diagnostics is most impressive, and I think it will also have great general appeal.

Thank you.

QUESTION: I understand the general concept that the surface tension will decrease with increase of the temperature. Do you have any quantitative or analytical description of the relationship between the temperature and the surface tension? Is this an exponential inverse or polynomial inverse? The second one is, if there is no such description, at what temperature will the surface tension be significantly decreased?

DR. OSTRACH: The answer is that we measured the surface tension even over long periods of time, because we knew that the oil would be put in the Shuttle and stay there for months. The answer is that you measure it. Also, the silicon oils are very well characterized. You can get that data from the manufacturers. You can either accept that or you measure it, as we did. You can almost get that custom made for you. So there is a whole range of silicon oils that you can get to give you most any kind of variation that you want.

QUESTION: Two brief comments, one to Dave [Larson] and the other to the two crystal growers [Dr. Larry DeLucas and Dr. David Larson].

In fact, I am a little bit surprised you didn't get any radial segregation. If I look at your free growth, it is not axially symmetric when you rotate it. That means heat input was not axisymmetric, which suggests an asymmetric curved interface. In turn, if I follow Sam Coriell's radial segregation effect, which you could check if the minor segregation effect fits the pattern of your asymmetry.

The second is a note of caution. I think the experiments, particularly by Dave, were just superb. They were superbly designed, analyzed, executed, everything. But a note of caution. I've heard "best crystal" and I've heard "ideally perfect crystal", and I think there may be justification for the terms, but the terms should always be in relation to the application. If you are talking application, as for example detector material, we have to go to parameters that are relevant. That means diffusion lens, carrier lifetime, carrier mobility. Have you done any of those, and what's the difference between your material and the material grown on ground?

The reason I'm saying that is, if you look at galium arsenide, and galium arsenide Bridgman grown, you can get material semi-insulating with a dislocation density of 1,000 to 2,000. In digital application the material is totally unsuitable because the conversion efficiency is about ten percent as opposed to 90 percent. So we have to take the terminology of perfection and quality evaluation in context with applications. Otherwise we have a problem, because it generates arguments. I talked to Hoover at the Max Planck Institute about certain experiments. I'm not going to tell you what he had to say about them, but it indicates you have to have convincing evidence in applications that you have superiority of properties, whatever it is.

DR. LARSON: Everything that Gus said is true. As far as trying to get it tested in a real system, we really did go to some great pains to try to get some of the flight material into a fabrication line for DARPA. Ultimately that effort failed. It wasn't because the material wasn't available. It's that they wanted to use it against a standard baseline process that was well understood, and they tried to get us in at the end of a batch where they could fabricate devices, if you will, on the substrates that we would provide. Ultimately, as I said, that effort failed and it hasn't been done. The material, from our standpoint, is still available, and we'd love to see those experiments run. If you have any suggestions in that line, we'd certainly like to cooperate.

With respect to your observation, regarding quantitative results, whether they are chemical or whether they are a structural defect, they can mislead at times. We tried to use a fairly exhaustive set of techniques to characterize these materials. I didn't have the time to go into everything that we have done. There has been a lot of each of the techniques that I mentioned. There has been a lot done on every set of those samples. So the database is pretty comprehensive, but falls short of device fabrication and testing.

As far as an overall detector application, you are absolutely right. We'd like to see those experiments done. If you can help us have that take place, I know you have good contacts with DARPA,we would be most appreciative. It is the only way to draw a final conclusion.

Appendix A: A History of Spacelab

Spacelab Missions in chronological order.

Year	Mission	Payload	Discipline	Hardware
1981	STS-2	Office of Space and Terrestrial Applications (OSTA-1)	Earth Science	Pallet
1982	STS-3	Office of Space Science (OSS-1)	Life Science, Multidisciplinary	Pallet
1983	STS-7	Office of Space and Terrestrial Applications (OSTA-2)	Microgravity	MPESS
1983	STS-9	Spacelab-1	Multidisciplinary	Module & Pallet
1984	STS-41D	Office of Applications and Space Technology (OAST-1)	Technology	MPESS
1984	STS-41G	Office of Space and Terrestrial Applications (OSTA-3)	Earth Science,Technology	Pallet & MPESS
1985	STS-51-B	Spacelab-3	Multidisciplinary	Module&MPESS
1985	STS-51-F	Spacelab-2	Multidisciplinary	Pallet & IPS
1985	STS-61A	Spacelab-D1	Life Science, Multidisciplinary	Module
1985	STS-61B	EASE/ACCESS	Technology	MPESS
1986	STS-61C	Microgravity Science Laboratory (MSL-2)	Microgravity	MPESS
1990	STS-35	ASTRO-1	Space Science	Pallet & IPS
1991	STS-40	Spacelab Life Sciences 1 (SLS-1)	Life Science	Module
1992	STS-42	International Microgravity Laboratory-1 (IML-1)	Life Science, Microgravity	Module
1992	STS-45	Atmospheric Laboratory for Applications and Science 1 (ATLAS-1)	Earth Science Space Science	Pallet
1992	STS-47	Spacelab-J (SL-J)	Microgravity, Life Science	Module
1992	STS-50	United States Microgravity Laboratory 1 (USML-1)	Microgravity	Module
1992	STS-52	United States Microgravity Payload (USMP)-1	Microgravity	MPESS
1993	STS-56	Atmospheric Laboratory for Applications and Science 2 (ATLAS-2)	Earth Science	Pallet
1993	STS-55	Spacelab-D2	Multidisciplinary	Module
1993	STS-58	Spacelab Life Sciences 2 (SLS-2)	Life Science	Module
1994	STS-59	Space Radar Laboratory 1	Earth Science	Pallet & MPESS
1994	STS-62	United States Microgravity Payload (USMP-2)	Microgravity	MPESS
1994	STS-65	International Microgravity Laboratory-2 (IML-2)	Microgravity, Life Science	Module
1994	STS-64	LIDAR In-space Technology Experiment	Technology Earth Science	Pallet
1994	STS-66	Atmospheric Laboratory for Applications and Science 3 (ATLAS-3)	Earth Science	Pallet
1994	STS-68	Space Radar Laboratory-2	Earth Science	Pallet & MPESS
1995	STS-67	ASTRO-2	Space Science	Pallet & IPS
1995	STS-71	Spacelab-Mir	Multidisciplinary, Logistics	Module
1995	STS-73	United States Microgravity Laboratory (USML-2)	Microgravity	Module
1996	STS-75	Tethered Satellite System (TSS-1R)/USMP-3	Microgravity	MPESS
1996	STS-78	Life and Microgravity Spacelab (LMS)	Microgravity, Life Science	Module
1997	STS-83	Microgravity Science Laboratory (MSL-1)	Microgravity	Module
1997	STS-87	United States Microgravity Payload (USMP-4)	Microgravity	MPESS
1997	STS-94	Microgravity Science Laboratory (MSL)-1R (reflight)	Microgravity	Module
1998	STS-90	Neurolab	Life Science	Module



Appendix B: Spacelab-A Synopsis

The Spacelab Module, exposed platforms, and supporting instrumentation were designed and developed by the European Space Agency to house advanced experiments inside the Space Shuttle cargo bay. The Spacelab program has hosted a cross-disciplinary research agenda over a 17-year flight history. Several variations of Spacelab were used to host payloads for almost every space research discipline that NASA pursues-life sciences, microgravity research, space sciences, and earth observation studies. After seventeen years of flight, Spacelab modules, pallets, or variations thereof flew on the Shuttle 36 times for a total of 375 flight days.

The Spacelab suite of hardware included four principle components:

1. The Spacelab Module is a pressurized, cylindrical facility 23 feet long and 13 feet wide that attached to the Orbiter within the Shuttle cargo bay. Internal research facilities were modular in nature, altered on a flight-by-flight basis to address the particular research requirements of each Spacelab Module research mission. Sixteen module flights supported over 600 investigations in the life and physical sciences.

2. The Spacelab Pallet was designed by ESA and its industrial partners for large instruments requiring direct exposure to space or systems needing unobstructed, broad fields of view. The U-shaped pallets were 13 feet wide and 10 feet long and were capable of supporting up to 3 tons in payload. Up to five pallets could be flown at a time. Twelve Pallet flights supported almost 100 investigations in Technology, Space Science, Earth Science, and the Life and Microgravity Sciences.

3. The Instrument Pointing System (IPS) was designed by ESA to provide a minimum of 2 arc seconds of pointing accuracy for Spacelab Pallet-mounted payloads. Three research missions utilized the IPS system to generate high-quality scientific returns for astronomy and astrophysics payloads.

4. The Mission-Specific Experiment Support Structure (MPESS) was built in the United States and managed as an integral component of the Spacelab research program. MPESS pallets support up to 3000 pounds of payload and can provide power, thermal control, and data handling capability. Twelve Spacelab flights flew payloads mounted on the adaptable



MPESS platforms to support a robust, cross-disciplinary research agenda.

Over almost two decades of flight, the Spacelab module and exposed platforms represented the most advanced Shuttle research facilities of their time. A Spacelab module was even flown to Mir to serve as a visiting laboratory during the 1st U.S.-Russian, Shuttle-Mir docking mission.

Research on Spacelab flights has been widely international. Scientific hardware contributors and Principle and Co-Investigators have participated from Australia, Belgium, Canada, France, Germany, India, Italy, Japan, Russia, Switzerland, the United Kingdom—and of course, the United States. Reflecting international leadership roles in the Spacelab program, Germany directed Spacelab payload operations for the Spacelab-D1 and D2 flights.

Spacelab research has been responsible for tremendous scientific and commercial research advances in life and microgravity space research. More than 750 Spacelab experiments resulted in over 1,000 refereed articles, 2,000 talks and abstracts, and 250 master's and doctoral theses. The Spacelab program has been one of the most successful space research programs in history.

Our experience with the Spacelab program has paved the way for research on the International Space Station. We have garnered important experience in multinational cooperation and data dissemination. We have learned to work together to improve research operations and results analysis. The international coordination required by Spacelab missions has been an excellent foundation for the high level of integration that is necessary for successful International Space Station research operations.

Moreover, we have garnered 17 years of experience conducting research in a laboratory environment 180 miles above the Earth in a crewed space vehicle. We have learned from our experience about what types of investigations work best in such an environment, and are applying that knowledge as we plan the initial stages of Station research.

Appendix C: Spacelab Mission Logos



STS-2 OSTA-1



STS-3 OSS-1



STS-7 OSTA-2



STS-9 Spacelab-1



STS-41D OAST-1



STS-41G OSTA-3



STS-51B Spacelab-3



STS-51F Spacelab-2



STS-61A Spacelab-D1



STS-61B EASE/ACCESS



STS-61C MSL-2



STS-35 ASTRO-1



STS-40 SLS-1



STS-42 IML-1



STS-45 ATLAS-1



STS-47 Spacelab J



STS-50 USML-1



STS-52 USMP-1



STS-56 ATLAS-2



STS-55 Spacelab-D2



STS-58 SLS-2



STS-62 USMP-2



STS-59 SRL-1



STS-65 IML-2



STS-64 LITE



STS-66 ATLAS-3



STS-68 SRL-2



STS-67 ASTRO-2



STS-71 Spacelab/Mir



STS-73 USML-2



STS-75 TSS-1R/USMP-3



STS-78 LMS



STS-83 MSL-1



STS-87 USMP-4



STS-94 MSL-1R



STS-90 Neurolab

Appendix D: Presenter Acronyms

ACISS	Advisory Committee on the International Space Station
ADH	Antidiuretic hormone
ADVASC	Advanced ASTROCULTURE™ Unit
AFM	Atomic Force Microscopy
AGHF	Advanced Gradient Heating Facility
AMPS	Atmosphere, Magnetosphere, and Plasmas in Space
ANF	Atrial natriuretic factor
AO	Announcement of Opportunity
APCF	Advanced Protein Crystallization Facility
ASC	Astroculture
ASTRO	Ultraviolet Astronomy Mission
ATLAS	Atmospheric Laboratory for Applications and Science
ATMOS	Atmospheric Trace Molecule Spectroscopy
ATV	Automated Transfer Vehicle
BDPU	Bubble, Drop and Particle Unit
BFU-E	Blood forming units
BIMDA	Bioserve/ITA Materials Dispersion Apparatus
BPL	BioServe Pilot Lab
BTS	Breedable Transformed Seed
CAAMP	Center for Advanced Microgravity Materials Processing
CCD	Configuration Control Document or Charge Coupled Device
CEBAS	Closed Equilibrated Biological Aquatic System
CEO	Chief Executive Officer
CF	Constant Flux
CFC	Chloroflurocarbon
CFU-E	Colony forming units
CGBA	Commercial Generic Bioprocessing Apparatus
CGF	Crystal Growth Furnace
CIDR	Critical Intermediate Design Review
CITE	Cargo Integration Test Equipment
CNES	Centre National d’Etudes Spatiales (French Space Agency)
COF	Construction of Facilities or Columbus Orbiting Facility
COLSA	A NASA contractor company
COSMOS	Early European Space Consortia
CPBF	Commercial Plant Biotechnology Facility
CPF	Critical Point Facility
CPU	Central Processing Unit
CSA	Canadian Space Agency
CT	Constant Temperature

CTC	Constant Temperature Configuration
CVP	Central venous pressure
DARPA	Defense Advanced Research Projects Agency
DASA	DaimlerChrysler Aerospace (present day)
DFVLR	Predecessor of DLR
DLR	Deutsches Zentrum für Luft- und Raumfahrt e.V. (German Space Agency)
DOD	Department of Defense
DSR	Database Support Request
DT	Dynamic Temperature
ECLS	Environmental Control and Life Support
EDOMP	Extended Duration Orbiter Medical Program
ELDO	European Launcher Development Organization
EGSE	Electrical Ground Support Equipment
EMC	Electromagnetic Compatibility
EMI	Electromagnetic Interference
EOM	Earth Observing Mission
EPD	Etch Pit Density
EPM	European Physiology Modules
EPO	Erythropoietin
EPS	Elite parent seed
ER	Early Release
ESA	European Space Agency
ERNO	A German company now part of DASA
ESRO	European Space Research Organization
ESTEC	European Space Research and Technology Centre
ETH	Swiss Federal Institute of Technology
EUE	Experiment Unique Equipment
EURECA	European Retrievable Carrier
EVA	Extra Vehicular Activity
FGBA	Fluids Generic Bioprocessing Apparatus
FNDS	Fluid and Nutrient Delivery System
FPA	Fluids Processing Apparatus
FPM	Fluid Physics Module
FSL	Fluid Science Laboratory
GAP	Group Activation Pack
GAS	Get Away Special
GEFA	Gas Exchange Fermentation Apparatus
GHF	Ground Handling Fixture or Gradient Heating Facility
GSE	Ground Support Equipment
GSFC	Goddard Space Flight Center
HCL	Hydrogen chloride
HF	Hydrogen fluoride
HPLC	High Performance Liquid Chromatography
HUT	Hopkins Ultraviolet Telescope
ICD	Interface Control Document or Drawing

ICM	Isothermal Containment Module
IDGE	Isothermal Dendritic Growth Experiment
IFSUSS	International Forum for the Scientific Uses of Space Station
IGA	Inter-Governmental Agreement
IGF1	Insulin-like growth factor-1
IGM	Intergalactic Medium
IL1	Interleukin-1
IML	International Microgravity Laboratory (IML-1 and IML-2)
IMSPG-	International Microgravity Strategic Planning Group
IMU	Inertial Measurement Unit
IPMP	Integrated Payload Mission Planning
IPS	Instrument Pointing Systems
IR	Infrared
ISAS	Institute of Space and Astronautical Science (Japan)
ISIS	Integrated Systems and Information Services
ISLSWG	International Space Life Sciences Working Group
ISS	International Space Station
JASMA	Japan Society of Microgravity Application
JEA	Joint Endeavor Agreement
JSAEM	Japan Society of Aerospace and Environmental Medicine
JSSS	Japanese Society of Sericultural Science
JPL	Jet Propulsion Laboratory
JSC	Johnson Space Center
JSLWG	Joint Spacelab Working Group
JURG	Joint User Requirements Group
KSC	Kennedy Space Center
LBNP	Lower Body Negative Pressure
LED	Light Emitting Diode
LiOH	Lithium hydroxide
LITE	Lidar in-Space Technology Experiment
LMSAAC	Life and Microgravity Sciences and Applications Advisory Committee
LSLE	Life Sciences Laboratory Equipment
MARES	Muscle Atrophy Research and Exercise System
MAS	Millimeter-wave Atmospheric Sounder
MBB	A German company now part of DASA
MCS	Modular Cultivation System
MDMs	Multiplexer-Demultiplexer
MESH	Early European Space Consortia
MIT	Massachusetts Institute of Technology
MMA	Microgravity Measurement Assembly
MOMS	Modular Optoelectronic Multispectral Scanner
MOU	Memorandum of Understanding
MPLM	Mini Pressurized Logistics Module
mRNA	Mitochondrial Ribonucleic Acid
MSDR	Materials Science Double Rack

MSFC	Marshall Space Flight Center
MSL	Materials Sciences Laboratory (MSL-1 and MSL-2)
NACA	National Advisory Committee for Aeronautics (Predecessor of NASA)
NASA	National Aeronautics and Space Administration
NASDA	National Space Development Agency of Japan
NIH	National Institutes of Health
NIST	National Institute of Standards and Technology
NOAA	National Oceanic and Atmospheric Administration
NRA	NASA Research Announcement
NRC	National Research Council
NSF	National Science Foundation
O&C	Operations and Checkout Building (KSC)
OD	Optical Density
OFT	Orbital Flight Test
OH	Hydroxide
OLMSA	Office of Life and Microgravity Science and Applications
OPERA	Orbital processing of Eutectic Rod-like Arrays
OPF	Orbiter Processing Facility (KSC)
OSS	Office of Space Science
OSTA	Office of Science and Terrestrial Applications
OTFE	Oscillatory Thermocapillary Flow Experiment
PACE	Physics and Chemistry Experiments
PAO	Public Affairs Office
PCDF	Protein Crystallisation Diagnostics Facility
PD	payload developer
PEMS	Percutaneous Electrical Muscle Stimulator
PGBA	Plant Generic Bioprocessing Apparatus
PIs	Principal Investigators
PL	Payload or Photoluminescence
POCC	Payload Operations Control Center
PR	Public Relations
PSA	Pre-sleep activity
PSG	Payload Support Group
PTH	Parathyroid hormone
RAAB	Remote Activation and Acquisition Box
RBC	Red Blood Cells
RMS	Remote Manipulator System
RNA	Ribonucleic Acid
ROTEX	Robotic Technology Experiment
RPI	Rensselaer Polytechnic Institute
SEPAC	Space Experiments with Particle Accelerators
SMURRF	Shared Multi User Remote Robotic Facility
SOLSPEC	Solar Spectrum
SPAS	Shuttle Pallet Satellite
SPICE	Spacelab Payload Integration Center in Europe

SPP	Science and Power Platform
SPRAG	Shuttle Payload Requirements and Analysis Group
SRB	Solid Rocket Booster
SSBUV	Shuttle Solar Backscatter Ultraviolet
SSPPSG	Space Shuttle Payload Planning Steering Group
SSUAS	Space Station Utilization Advisory Subcommittee
STAR	Early European Space Consortia
STDCE	Surface Tension Driven Convection Experiment
STS	Space Transportation System
TDRSS	Tracking and Data Relay Satellite System
TDSE	Transient Dendritic Solidification Experiment
TEACH	Thermal Equilibrium and Chemical Homogeneity
TEMPUS	Tiegelfreies Elektromagnetisches Prozessieren Unter Schwerelosigkeit (Electromagnetic Containerless Processing Facility)
TMS	The Minerals, Metals, and Materials Society
TOMS	Total Ozone Mapping Spectrometer
TRW	A NASA contractor company
TVD	Torque Velocity Dynamometer
UAB	University of Alabama at Birmingham
UAH	University of Alabama in Huntsville
UARS	Upper Atmosphere Research Satellite
UIT	Ultraviolet Imaging Telescope
USDA	United States Department of Agriculture
USML	United States Microgravity Laboratory (USML-1 and 2)
USMP	United States Microgravity Payload (USMP-1, -2, -3, -4)
USUHS	University Services, University of the Health Sciences
UV	Ultraviolet
VAFB	Vandenberg Air Force Base
VVIS	Visual and Vestibular Investigation System
WCSAR	Wisconsin Center for Space Automation and Robotics
WUPPE	Wisconsin Ultraviolet Photo-Polarimeter Experiment

Appendix E: Participant Biographies

Dr. Kenneth Baldwin

Dr. Baldwin has been a professor in the Department of Physiology and Biophysics at the University of California, Irvine since 1973. From 1989-1996, he also served as Senior Associate Dean For Academic Affairs at the College of Medicine, University of California, Irvine. Dr. Baldwin received a B.S. degree (Magna Cum Laude)in Physical Education from Springfield College; an M.S. in Physical Education from the University of Massachusetts; and a Ph.D in Exercise Physiology from the University of Iowa. He has also been awarded numerous NASA and National Institute of Health grants. In addition, he has served on various national advisory committees to include the NASA Life and Biomedical Sciences Advisory Subcommittee (Chair, 1992-1999), NASA-NIH Biomedical and Behavior Advisory Committee (1993-2000), and the American College of Sports Medicine Research Advisory Committee (chair; 1996-1999). Dr. Baldwin has published 130 peer reviewed articles, and 15 book chapters and review articles.

Mr. Klaus Berge

Director of Space Projects at Deutsches Zentrum für Luft- und Raumfahrt (DLR) e.V., Bonn, Germany, since 1997, Mr. Berge previously served as the Managing Director and Deputy Director General at Deutsche Agentur für Raumfahrtangelegenheiten (DARA) GmbH, Bonn, Germany, as well as Chairman of the ESA Programme Board Manned Space. He is a Certified Engineer (Dipl.-Ing.), AerospaceTechnical University, Berlin, Germany, and is the Founder and President of the R + I System GmbH, Bremen, Germany, a space consulting company. He has thirty-two years of space related national and international experience in industry as well as government.

Mr. Robert Benson

Mr. Benson served as a consultant to NASA from 1993 to 1995 on scientific instrument development for the Space Station. Prior to this, from 1985 to 1993, he was the Director of the Flight Systems Division in the Office of Space Science and Applications. Mr. Benson received a Bachelors degree in Mathematics (Magna Cum Laude) from the University of South Dakota, a Masters degree in Mathematics from the University of South Dakota, and a Masters degree in Public Administration from Indiana University. He has been awarded a National Science Foundation Fellowship (1960-61); four NASA Exceptional Service Medals for his work with the Apollo, Skylab, and Spacelab programs; and a Presidential Meritorious Service Award (1991), along with other awards and letters of commendation. Mr. Benson is the author of many papers and articles related to orbit determination, satellites, and mission operations. He is a member of Phi Beta Kappa, Sigma Xi, Pi Mu Epsilon, and Eta Sigma Phi honorary societies.

Dr. Horst Binnenbruck

Dr. Binnenbruck received his doctorate from the University of Cologne, Germany in 1973. Since 1974 he has been an employee of the German Aerospace Center DLR, working for two years as a researcher, then as

project manager in the DLR Project Executive Department. From 1986-1990 he was the Head of Microgravity Research and Life Sciences Branch; from 1990-1997 he was Head of the Microgravity Research and Life Sciences Division at the German Space Agency/DARA. From 1998 to the present he has been the Head of Projects for Microgravity Research and Life Sciences. He served as science coordinator on Spacelab Mission 1 for the Materials Science Double Rack, and on the German Spacelab Mission, D-1, for the entire payload. Following those missions he has had program responsibility for almost all German Spacelab experiments in the field of microgravity research and life sciences.

Dr. Bradley Carpenter

Dr. Carpenter received his Ph.D. in Chemical Engineering from Stanford University in 1987. His doctoral research with George Homsy dealt with thermocapillary flows. He received his B.S. in Chemistry from the University of California, Berkeley, where he did research with Paul Modrich on E. coli bacteriophage replication. He also has an M.S. in Chemical Engineering from the University of Virginia, where his thesis work with Doug LeVan examined purification processes in gas absorption beds. His experience in industry includes work with the Borden Chemical Company, the Chevron Chemical Company, and E. Mitchell, Inc., a mechanical contractor based in San Francisco.

Dr. Carpenter began his work with NASA in 1988 as a senior staff scientist with the Bionetics Corporation, a contractor providing support services to the Microgravity Science and Applications Division. He joined NASA in 1990 as the program scientist for the biotechnology, combustion science, and fluid dynamics and transport phenomena disciplines. In 1996 he was named lead scientist for the division. As Lead Scientist he is responsible for coordinating policy, strategy, and budget for the five disciplines (materials science, biotechnology, combustion science, fundamental physics, and fluid physics) of microgravity research, as well as international cooperation and planning for NASA's microgravity research on the International Space Station as the NASA co-chair of the International Microgravity Strategic Planning Group. The program supports nearly 500 research investigations at over 100 universities and laboratories, and reviews over 400 research proposals annually.

Mr. Harry G. Craft Jr.

Harry G. Craft is the Vice President, Information Systems with COLSA Corporation, a major aerospace contractor, in Huntsville, Alabama. Prior to this position, Mr. Craft had a distinguished career at NASA's Marshall Space Flight Center, retiring after 39 years of service. While at Marshall, Mr. Craft served in numerous positions including Assistant Director, Science and Engineering; Manager of Technology Transfer Office and Manager of Payload Projects Office. In this later capacity, Mr. Craft was involved in the management of numerous Spacelab Flights from 1983-1994 in virtually every Science, Application, and Technology discipline. Mr. Craft has been honored as a NASA Meritorious Executive; received the Agency's Distinguished Service and Outstanding Leadership Medals for performance associated with the Spacelab Program; received the 1997 Electrical Engineering Outstanding Alumni Award and the 1995 Distinguished Auburn Engineer Award from Auburn University; received the 1995 Holger N. Toftoy Award from the Alabama-Mississippi Section of the American Institute of Aeronautics and Astronautics (AIAA) for outstanding technical management; and was named the 1993 Manager of the Year by the local chapter of the National Management Association. Mr. Craft earned a Bachelor of Science degree in Electrical Engineering from Auburn University in 1964 and received a Master's Degree in 1977 in Administrative Sciences from the University of Alabama in Huntsville.

Dr. Roger K. Crouch

Dr. Crouch is currently on loan to NASA, Office of Life and Microgravity Sciences and Applications (OLMSA) where he serves as the Senior Scientist. For the three years prior to that he trained and flew as a Payload Specialist for the Microgravity Science Laboratory mission. This was a Spacelab flight which was launched in April 1997 in a mission that was terminated early for mechanical reasons and then launched again in July 1997 for the full sixteen day mission. Prior to that Dr. Crouch served as the Lead Scientist for the Microgravity Science and Applications Division of OLMSA for 10 years. In that role he served at various times as the program scientist for five Spacelab flights. The years before that were spent as a Researcher at the Langley Research Center in Hampton, VA. When he left Langley, he was a Principal Investigator on a space flight research experiment investigating the role of gravity on the growth and properties of II-VI and IV-VI semiconductor materials. Dr. Crouch received his BS from Tennessee Tech, his MS and PhD from Virginia Tech. He was a visiting scientist at the Massachusetts Institute of Technology in 1979-80, where he worked with Prof. A. Witt.

Dr. Arthur Davidsen

Arthur F. Davidsen is Professor of Physics and Astronomy at the Johns Hopkins University and a member of the principal professional staff of the university's Applied Physics Laboratory where, in 1977, using a unique new remote-controlled, rocket-borne telescope and spectrometer launched from the White Sands Missile Range, he obtained the first ultraviolet spectrum of an object beyond our Galaxy - the quasar 3C273. He was the Principal Investigator on the NASA-funded Hopkins Ultraviolet Telescope (HUT) project, and also directed the design and development of the optics for the Faint Object Spectrograph on the Hubble Space Telescope. Professor Davidsen was educated at Princeton University (A.B. 1966) and the University of California, Berkeley (M.A. 1972, Ph.D. 1975). He has been the recipient of several awards, including the prestigious Helen B. Warner Prize of the American Astronomical Society in 1979 and a Johns Hopkins University Presidential Citation in 1991. An Alfred P. Sloan Foundation Fellow from 1976 to 1980, Davidsen was elected a Fellow of the American Association for the Advancement of Science in 1984, chairman of its Astronomy Section in 1989, and a Fellow of the American Physical Society in 1996.

Dr. Lawrence DeLucas

Dr. DeLucas received a bachelor of science degree in Chemistry in 1972; a masters degree in Chemistry in 1974; a bachelor of science degree in Physiological Optics in 1979; a doctoral degree in Optometry in 1981; and a Ph.D. degree in Biochemistry in 1982. All degrees were awarded by the University of Alabama at Birmingham. He is a Professor in the School of Optometry with secondary appointments in the Departments of Biochemistry and Molecular Genetics, Biophysics and Chemistry. Dr. DeLucas is the Director of the Comprehensive Cancer Center X-ray Core Facility and of the Center for Macromolecular Crystallography (CMC) at UAB. He holds positions as Senior Scientist at UAB in the Comprehensive Cancer Center, the Research Center in Oral Biology and the Vision Science Research Center. He is an Adjunct Professor in the UAB Departments of Biochemistry and Molecular Genetics, Laboratory of Medical Genetics, the Department of Materials Science and the Department of Chemistry. Dr. DeLucas' research interests involve the investigation of the three-dimensional structure of molecules of biological importance. Some of the specific applications include the development of new pharmaceutical compounds for the treatment of patients with diabetes, AIDS, cancer, cardiovascular problems, influenza, and malaria. His research has also involved fundamental studies in protein crystal growth. As part of this overall effort, a series of

microgravity experiments are being performed on Space Shuttle flights. Dr. DeLucas has published over 80 research articles in various scientific journals and co-authored two books on protein crystal growth. He is the recipient of many American and international awards. He served as a Payload Specialist for the first United States Microgravity Laboratory mission which was launched on June 25, 1992. He is also a co-inventor on three patents involving protein crystal growth hardware and techniques and recently received a NASA Research Award for hardware that he designed for protein crystal growth experiments in space.

Dr. Mary Anne Frey

Mary Anne Frey, Ph.D., was Program Scientist for the Neurolab Spacelab mission. As a scientist with NASA's Life Sciences Division, she was also Program Manager for the Physiology and Countermeasures Research Program and Program Scientist for the Human Research Facility of the International Space Station. She collaborated with the U.S. National Institutes of Health and National Science Foundation and with international space agencies on numerous projects. Prior to this assignment, she was a manager with Lockheed Engineering and Sciences Company in Washington, D.C., and worked as a research scientist and manager at Johnson Space Center and Kennedy Space Center. Before she joined the space program, Dr. Frey was a faculty member in the Department of Physiology at the Wright State University School of Medicine. Dr. Frey was awarded the Astronaut's "Silver Snoopy" Award for her work on Neurolab and was a recipient of the NASA Group Achievement Award for the Neurolab Mission. She received the Louis H. Bauer Founders Award of the Aerospace Medical Association (AsMA); the Strughold Award of the AsMA Space Medicine Branch, and the Ellingson Literary Award of the AsMA Associate Fellows. She was elected a Fellow of the AsMA and a Member of the International Academy of Astronautics. She has served as a consultant and has been on editorial boards of several professional journals. She is the author of numerous manuscripts, book chapters, and presentations on space physiology, cardiovascular physiology, and exercise and stress physiology. Dr. Frey earned a Bachelor of Arts degree in Physics from the George Washington University in 1970 (where she was elected to Phi Beta Kappa), a Ph.D. degree in Physiology from the George Washington University in 1975, and an M.B.A. degree from Florida Institute of Technology in 1984. She has recently returned to Wright State University as Professor in the Department of Community Health, where she teaches space physiology to Residents in Aerospace Medicine and is continuing with space life sciences activities.

Dr. Rod Hughes

Dr. Rod Hughes received his Ph.D. in cognitive and behavioral neuroscience from Bowling Green State University in Ohio. While in Ohio, he studied the effects of melatonin on sleep (a topic related to his later research on Neurolab). He conducted postdoctoral research at the Oregon Health Sciences University and became an Assistant Professor there. Later, he was Director of the Clinical Biology and Sleep Laboratory at Brooks Air Force Base for the U.S. Air Force. Dr. Hughes is now a faculty member at Harvard Medical School, where he is a co-investigator on the Neurolab STS-90 sleep experiment, as well as on the sleep experiment that was performed on the STS-95 flight.

Dr. Jack Kaye

Dr. Kaye currently serves as the Director of the Research Division of NASA's Office of Earth Science and the Manager of the Atmospheric Chemistry Modeling and Analysis Program in NASA's Office of Earth Science. Prior to this he worked as a space scientist at NASA's Goddard Space Flight Center. Dr. Kaye has

served as a program scientist for the ATLAS series of Shuttle missions and the Total Ozone Mapping Spectrometer and Stratospheric Aerosol and Gas Experiment series of satellite instruments. He was co-chair of two subgroups of the US Global Change Research Program - one on atmospheric chemistry and ozone, the on UV Radiation Monitoring and Effects, and was elected by his peers to serve as co-secretary of the Atmospheric Sciences Section of the American Geophysical Union. He has also edited the book Isotope Effects in Gas-Phase Chemistry for the American Chemical Society (published 1992). He received a B.A. in chemistry from Adelphi University (summa cum laude), and a Ph.D. in chemistry from the California Institute of Technology. He has received the NASA Exceptional Achievement Medal (1995), the NASA Exceptional Service Medal (1996), and the TERRA Award of the NASA Office of Mission to Planet Earth (1995).

Mr. Joel Kearns

Joel Kearns is currently Director, Crystal Growing Technology, and Acting Vice President, Engineering and Technology, at Mitsubishi Silicon America of Salem, Oregon, a global supplier of prime polished and epitaxial Silicon wafers to the international electronics industry. Prior to joining MSA in June 1999, Kearns was the Manager, Microgravity Research Program Office, NASA Marshall Space Flight Center in Huntsville, Alabama. In this capacity, he served as senior NASA official for the Agency Mission Assignment of Microgravity and managed the National Microgravity Research Program and Space Product Development Program. The Microgravity Research Program Office leads, directs and manages all NASA sponsored scientific, technological and commercial research work in physics, chemistry and engineering science in weightlessness. The MRPO utilizes Commercial Space Centers, NASA Field Centers, universities and government laboratories. The two NASA Programs implement the objectives of the Human Exploration and Development of Space Strategic Enterprise, generating new knowledge and communicating that knowledge to all customers and stakeholders. Kearns formed the organization in 1996. Prior to joining MSFC in 1995, Kearns was Manager of the Microgravity Materials Science and Biotechnology Flight Programs at NASA Headquarters' Office of Life and Microgravity Sciences and Applications. He joined NASA at that office in 1988, and provided executive level direction for crystal growth research and associated apparatus and instrumentation development. Before working for NASA, Kearns was a member of the "Semiconductor Materials Processing in Space" group at Grumman Aerospace, where he contributed to the development of programmable multizone furnaces for crystal growth from the melt of compound semiconductors in space and on Earth. He holds a Bachelor of Science degree from Worcester Polytechnic Institute, Worcester, Massachusetts, and is completing degree requirements for a Master of Science degree from that same institution. Kearns received over thirty Certificates of Appreciation for leadership and facilitation of scientific and engineering research while at NASA, in addition to numerous Group Achievement and Sustained Superior Performance Awards and the NASA Astronauts' Personal Achievement Award. He is a member of the American Association for Crystal Growth and Sigma Xi: The Scientific Research Society.

Dr. David Klaus

Dr. Klaus obtained his B.S. in Mechanical Engineering from West Virginia University in December 1984. He received his M.S. in Aerospace Engineering Sciences in 1991 and his Ph.D. in 1994 at the University of Colorado, Boulder. He has worked at Kennedy Space Center as a Shuttle life support systems engineer and later was assigned to a team tasked with preparing the facilities at Vandenberg, CA for polar orbit Shuttle

launch activities that were anticipated to begin in 1986. From 1987-1990 he worked at the Johnson Space Center where he evaluated advanced space suit prototypes and planned Space Station EVA operations. While a graduate student at the University of Colorado he joined BioServe Space Technologies as a Research Assistant in 1990. His roles in BioServe's space flight program included developing payload operating procedures, crew training, payload integration and mission support for seven Shuttle missions flown between 1991-1994. Dr. Klaus developed a new course in 1993 entitled Introduction to Space Life Sciences and continues to instruct it annually. He has served as a volunteer for Denver area K-12 outreach programs since 1992. He spent one year after graduation as a visiting scientist at the German Aerospace Research Establishment (DLR) in Cologne on a Fulbright Scholarship and returned to the University of Colorado in 1995 as a Research Associate. He is responsible for managing BioServe payload operations on Shuttle and Mir and forming collaborations with the pharmaceutical industry to explore applications of space flight bioprocessing. His primary research interest entails developing engineering models to understand how biological processes are affected by reduced-gravity. He was an astronaut candidate finalist in the 1998 selection and was appointed as an Assistant Professor (Attendant Rank) in the Aerospace Engineering Sciences Department at the University of Colorado in 1998.

Dr. Matthew Koss

Dr. Koss received his A.B. degree from Vassar College in 1983 and his Ph.D. in Experimental Condensed Matter Physics from Tufts University in 1989. He joined the Materials Science and Engineering Department of Rensselaer Polytechnic Institute in 1990 as a Postdoctoral Research Associate and later was appointed to the faculty as a Research Assistant Professor. At Rensselaer, Dr. Koss has served as the Lead Scientist for the Isothermal Dendritic Growth Experiment (IDGE), a basic microgravity research project on dendritic solidification that conducted Space Shuttle flight experiments on STS-62, STS-75, and STS-87. Currently, Dr. Koss is the Principal Investigator of the Transient Dendritic Solidification Experiment (TDSE), being prepared for operations on the International Space Station in 2004. Dr. Koss is the author or co-author of over 50 technical papers and has prepared or presented over 100 technical talks. Dr. Koss is a member of the AIAA, APS, MRS, Sigma Xi, and TMS and serves on the AIAA Technical Committee on Microgravity and Space Processes. Recently, Dr. Koss has been selected as an AIAA Distinguished Lecturer. In addition to these research activities, Dr. Koss has been heavily involved in outreach and education. He developed and organized a two-week workshop to introduce local K-12 teachers to microgravity science, and has continued to work with and involve area teachers, their students, and the local community in learning about science, engineering, and NASA's microgravity program. In Fall 1999 Dr. Koss will be teaching Introductory Physics in Rensselaer's newly instituted Laptop Computing Program.

Dr. David J. Larson, Jr.

Dr. Larson obtained BE and MS degrees from Stevens Institute of Technology and his Ph.D. from Northwestern University. He joined the Corporate Research Center of the Grumman Corporation in 1969, where he was affiliated for 26 years. He initially worked at Grumman on specific aircraft applications involving shape-memory (smart) materials (which was his thesis topic at Northwestern University), Sn-coated copper wire aging, and eutectic brazements for titanium structures. In 1972 he began a long, continuing collaboration with the Microgravity Science and Applications Division of NASA, studying the influences of gravitational phenomena (hydrostatic and buoyant) on solidification and crystal growth. He has conducted microgravity solidification experimentation in drop tubes and towers, aircraft flying low-gravity

Keplerian arcs, sub-orbital sounding rockets, and orbital vehicles: Skylab in 1972/73; the Apollo-Soyuz Test Project in 1975; and in the Space Shuttle during STS Missions 51G, 61C, and 26. These microgravity experiments concentrated on gravitationally-dependent influences on the solidification of high-performance magnetic materials and involved detailed thermal, thermo-solutal and in-situ temperature measurements as well as microstructural and physical property analyses. This evolved into the study of gravitational influences on seeded Bridgman Stockbarger crystal growth of doped and alloyed CdTe compound semiconductor crystals for infrared detector applications, on STS Missions 50 and 73. These experiments involved the comparative analysis of CdZnTe crystals grown in the Crystal Growth Furnace (CGF) in the First (STS-50) and Second (STS-73) U. S. Microgravity Laboratory (USML-2) Missions. These crystals, grown in microgravity without ampoule wall contact, are virtually devoid of pervasive defects called twins, and have dislocation defect densities two orders of magnitude lower than the best terrestrial CdZnTe detector crystals.

Dr. Larson was selected by NASA to develop a flight experiment entitled “Orbital Processing of Eutectic Rod-like Arrays” (OPERA) in June 1996. This flight opportunity has been augmented by the selection of a preliminary glovebox flight experiment entitled “Thermal Equilibrium and Chemical Homogeneity” (TEACH). These experiments focus on simultaneous precision measurement of interface temperature, thermal gradients and cooling rates, processing velocity, and solidification structure and chemistry of eutectic alloys.

In June 1995 Dr. Larson left the Northrop-Grumman Applied Technology and Development Center and joined the staff of the Materials Science and Engineering Department of the State University of New York at Stony Brook. He has been added to the Departmental Design and Graduate Committees, teaches the senior design course entitled “Manufacturing, Materials and Technology” and continues to conduct his NASA-sponsored research. He is also chairman of the NASA Space Station User Advisory Subcommittee (SSUAS) and a member of the NASA Advisory Committee on the International Space Station (ACISS), Life and Microgravity Sciences and Applications Advisory Committee (LMSAAC), and the International Forum for the Scientific Uses of Space Station (IFSUSS).

Dr. Arnauld E. Nicogossian

Dr. Arnauld E. Nicogossian serves in a dual capacity with the National Aeronautics and Space Administration (NASA) as its Chief Medical Officer and Acting Associate Administrator for Life and Microgravity Sciences and Applications (OLMSA). Focus areas include life sciences, physical sciences, life support technology, biotechnology, aerospace medicine, occupational health, and commercial programs as they pertain to the conducting of experiments on the ground and in space.

OLMSA supports over 900 research grants throughout the country, at university, industry, and government laboratories. The program also encompasses the development and operation of a complex and unique set of research facilities. Essential to further the goal of the program is national and international cooperation. OLMSA has cooperative agreements with the National Institutes of Health, the National Science Foundation, the Department of Energy as well as the National Space Agencies of Japan, France, Canada, Italy, Germany and the European Space Agency. The Program currently relies on the Space Shuttle for short duration missions and on the International Space Station for the conduct of its future flight experiments.

Dr. Nicogossian's interests are directed primarily toward understanding human responses to extreme environments (spaceflight) and developing measures for protection and transfer this knowledge to benefit life on Earth. He has served NASA in the capacity of a cardiopulmonary researcher and space crews physician.

In addition to his work with NASA for more than twenty-seven years, Dr. Nicogossian holds an academic position as an Assistant Professor with the Department of Preventive Medicine and Biometrics of the Uniform Services University of Health Sciences, Bethesda, Maryland.

As an entrepreneur, Dr. Nicogossian co-founded and operated, from 1984-1991, the Fairfax Immediate Medical Care Partnership in Fairfax, Virginia.

Dr. Nicogossian is a member of many professional societies. He is a fellow of the American Astronautical Society, a fellow of the Aerospace Medical Association, a member of the International Academy of Astronautics and the American College of Physicians, and a Foreign member of the Academy of Sciences of the Republic of Armenia.

An author of more than forty scientific articles and a contributor to more than ten books, Dr. Nicogossian received his medical degree from Teheran University, trained in internal medicine at Mt. Sinai Hospital Services (Elmhurst) in New York City and has a Master of Science Degree from Ohio State University. He is a diplomat of the American Board of Preventive Medicine (Aerospace Medicine) and has been recognized by numerous awards from within and outside NASA. Among his many awards are the NASA Distinguished Service Medal (NASA's highest award), the Russian and the Ukrainian Federations of Cosmonautics Medals. He is past president of three medical and engineering societies.

Dr. Simon Ostrach

Dr. Ostrach received his B.S. degree with honors in Mechanical Engineering in 1944 and his M.E. degree in 1949 from the University of Rhode Island. In 1949 he received the Sc.M. degree in Applied Math and in 1950 the Ph.D. in Applied Math from Brown University. He has received numerous national and international awards and honors, and is a member of many professional organizations including Sigma Xi and Tau Beta Pi. His activities include being Home Secretary of the National Academy of Engineering and a member of the Board of Governors of the National Research Council. He has authored over 148 articles and papers in scientific and engineering journals and volumes as well as serving on numerous editorial boards. He has supervised 35 Ph.D. candidates and 31 M.S. candidates. Dr. Ostrach's career began in 1944 as Aeronautical Research Scientist at NACA (the predecessor of NASA). He was Chief, Fluid Physics Branch, NASA from 1950-1960. From 1960-1970 he was Professor of Engineering and Head, Division of Fluid, Thermal, and Aerospace Sciences, Case Institute of Technology (now Case Western Reserve University). From 1970 to the present he has been the Wilbert J. Austin Distinguished Professor of Engineering, Case Western Reserve University. Since 1997 he has been the Director of the National Center for Microgravity Research on Fluids and Combustion.

Mr. Werner Riesselmann

Mr. Riesselmann graduated as a telecommunications engineer from Technical University, Berlin, Germany. In 1970 he joined ERNO Raumfahrttechnik, Bremen, Germany where for three years he worked on

European launchers, for six years (1973-1979) he worked on Spacelab development and was responsible for the electrical ground support equipment, for six years (1979-1985) he worked on Spacelab Utilization (SL-1 and D-1) among others projects. He was project manager for integration, test and operations of the European payload on Spacelab-1. In 1986 he joined ESA's European Space Research and Technology Center (ESTEC) in the Netherlands as Section Head in the Microgravity Payloads Division. For ten years (1986-1996) he was responsible for development and operations (among other things on Spacelab, Spacehab, and EURECA) of materials science and fluid physics multi-user facilities. Since 1996 he has been Head of the Microgravity Payloads Division within ESA's Directorate of Manned Spaceflight and Microgravity. He is responsible for microgravity facilities and experiments on drop towers, parabolic flights, sounding rockets and orbiting spacecraft.

Dr. Muriel Ross

Dr. Ross holds the position of Senior Scientist and the Director of the Center for Bioinformatics (formerly known as the Center for Biocomputation), which she founded at NASA's Ames Research Center in 1986. Prior to this she was a professor in the Department of Anatomy and Cell Biology at the University of Michigan Medical School. She has participated in three space flights studying the structure and function of gravity sensors of the inner ear. Among her honors and awards are the Elizabeth C. Crosby Award for Excellence in Teaching, 1977; the Fogarty International Fellowship for study at Oxford University, 1981; NASA Medal for Exceptional Scientific Achievement, 1990; and the FDA's Group Recognition Award as a member of the National Center for Toxicological Research Three-Dimensional Imaging, Reconstruction and Animation Project, in 1996.

Mr. Axel Roth

Mr. Roth is the Director of the Flight Projects Directorate at NASA's George C. Marshall Space Flight Center in Huntsville, Alabama. In this capacity, he is responsible for the project management, design, development, integration, testing, and operations of ground and flight operations for the International Space Station (ISS). Included within these tasks are responsibility for the management of the development of Node 2 and 3, the Environmental Control system; Multi-Purpose Pressurized Logistics Module oversight; development/integration of the Spacelab pallet as an unpressurized carrier for ISS assembly flight; and ISS utilization activities including payload operations and development of multi use hardware such as the EXPRESS Rack and pallet. These extensive efforts managed by Mr. Roth play a key role in the development and utilization of the International Space Station.

Mr. Roth has had a long and distinguished career spanning 40 years with the Marshall Space Flight Center. From 1960 until 1971, he worked as a Structures Engineer and later a Systems Engineer in the Apollo/Saturn program. From 1971 until 1974, his major assignments included systems engineering and operations activities for the Skylab program. From 1974 to 1981 he worked in the Marshall Center's Spacelab Program Office, and in 1981 he became Payload Operations Director for the Spacelab-2 Mission. He was named Manager of the Operations Office in the Space Station Projects Office in 1985, and in 1987 he was Manager of the Habitability Module Office. In 1989, he was named Chief Engineer of Spacelab Payload Integration for the Payload Projects Office. In 1991 he was named Deputy Manager of the Space Station Projects Office and in 1994 he assumed the position of Deputy Director of Program Development, becoming director in March 1995. He assumed the acting Manager position in the Flight Projects Office in December 1998, and was named Director of Flight Projects Directorate in May 1999.

Mr. Joseph H. Rothenberg

Joseph H. Rothenberg was named Associate Administrator of NASA for Space Flight, Washington, DC, on January 8, 1998, placing him in charge of NASA's Human Exploration and Development of Space. Mr. Rothenberg holds a Bachelor of Science degree in Engineering Science and a Master of Science degree in Engineering Management from C. W. Post College of the Long Island University. He served as the Director of NASA's Goddard Space Flight Center since July of 1995, and from 1990 to 1994, he was Associate Director of Flight Projects for the Hubble Space Telescope (HST) at Goddard. In 1997 he was awarded an Honorary Doctorate in Engineering from Stevens Institute of Technology. He is a member of the American Institute of Aeronautics and Astronautics and past president of the Long Island Section of the Instrument Society of America. Mr. Rothenberg was the recipient of the NASA Exceptional Service Medal in 1990, the NASA Distinguished Medal in 1994, and the NASA Outstanding Leadership Medal and the Senior Executive Service Presidential Rank Meritorious Executive Award in 1995. In 1997, he received the Presidential Rank Distinguished Executive Award. Rothenberg has also received the National Aviation Association Collier Trophy, the AIAA Goddard Astronautics Award, the National Space Club's Nelson P. Jackson Award, and was inducted into the Smithsonian's Aviation Week and Space Technology Hall of Fame.

Dr. Albert Sacco

Dr. Sacco received a bachelor of science degree in Chemical Engineering with honors from Northeastern University, Boston, Massachusetts, in 1973 and a doctorate in Chemical Engineering from the Massachusetts Institute of Technology, Cambridge, Massachusetts, in 1977. He was a Professor at Worcester Polytechnic Institute, Worcester, Massachusetts, for 20 years and was the Department Head for Chemical Engineering for nine years. Dr. Sacco joined the faculty of Northeastern University, Boston, Massachusetts in June, 1997 where he is the George A. Snell Distinguished Chair of Engineering. He is also the Director of the Center for Advanced Microgravity Materials Processing at Northeastern University. Dr. Sacco is the Principal Investigator for the Zeolite Crystal Growth experiments. The ZCG experiments were flown on the STS-50, SpaceHab, and STS-73 missions and are currently scheduled to fly on the International Space Station and Space Shuttle flights during 1999 and through 2003. He has been the Principal Investigator for more than 200 zeolite experiments performed in space; and has conducted over 50 of these in space himself. Dr. Sacco is one of only two scientists who have performed protein crystallization and optimized their formation in low-Earth orbit. He was selected as an alternate payload specialist for STS-50 (1991) and flew as a payload specialist on STS-73, which launched on October 20, 1995. The 16-day mission aboard Columbia focused on materials science, biotechnology, combustion science, and fluid physics contained within the pressurized Spacelab module. Dr. Sacco is the recipient of many awards and has over 120 publications (including book chapters) in the areas of carbon filament initiation and growth, catalyst deactivation, zeolite synthesis, and microgravity materials processing.

Mr. John D. Schumacher

Mr. Schumacher is NASA's Associate Administrator for External Relations. Prior to this he was with the law firm of Rogers & Wells, New York, NY, in a general corporate practice, and served in the United States Navy as the Personal Aide and Administrative Assistant to the Director, Navy Space, Command and Control; as a White House Social Aide from 1983-1984; an Intern in the Command, Control, and Communications Systems Directorate of the Joint Chiefs of Staff from 1982-1983; and Flagship Communications

Officer and Officer of the Deck for General Quarters and Special at-sea evolutions aboard USS GUADALCANAL (LPH-7) during deployments with Second, Sixth and Seventh Fleets from 1978-1982. Mr. Schumacher graduated with distinction from the United States Naval Academy, earning a B.S. in oceanography/general engineering, in 1976. He earned an M.A. in government, with a certificate in national security studies, from Georgetown University, in 1984. Mr. Schumacher earned a J.D. from the Columbia University School of Law, and a certificate with honors in international law from that university's Parker School of International and Foreign Law, in 1987. He is a member of the New York Bar, the America Bar Association (International Law Section) and the U.S. Naval Institute. Mr. Schumacher has been awarded the NASA Medal for Outstanding Leadership in 1996; the Presidential Rank of Meritorious for 1995; the Joint Service Commendation Medal; two Navy Commendation Medals; the Navy Achievement Medal; the Navy Expeditionary Medal; two Meritorious Unit Commendations; and the Battle Efficiency "E", among others.

Dr. Louis Stodieck

Dr. Stodieck obtained his Ph.D. in 1985 from the University of Colorado, Boulder in Aerospace Engineering Sciences with an emphasis in bioengineering. From 1985-1987 he held a postdoctoral fellowship from the Medical Research Council of Canada to conduct research in the Department of Physiology at the University of British Columbia, Vancouver. His research focused on the role of intracellular calcium in neuronal cell death caused by excitatory amino acids. In late 1987 he accepted a position as Associate Director for Technical Affairs with BioServe Space Technologies and he was appointed as Associate Research Professor at the University of Colorado, Boulder in 1995. He is responsible for managing BioServe's flight programs including development and operations of various life science payloads flown on KC-135 aircraft, sounding rockets, the Shuttle, Mir Space Station and now the International Space Station. Dr. Stodieck has provided management for over 25 payloads that were successfully flown on 13 Shuttle missions and two Mir Station increments. He has provided technical support and management for a variety of commercial development projects in conjunction with industry and university partners. He has directed research conducted by several graduate and undergraduate students in such areas as physiological effects of microgravity and applications of microgravity in biomaterials processing and biotechnology.

Dr. Frank M. Sulzman

Dr. Frank M. Sulzman received a B.S. in Biology from Iona College in New Rochelle, New York in 1967 and a Ph.D. in Molecular and Cell Biology from the State University of New York at Stony Brook in 1972 where he was an NIH pre-doctoral fellow. He was an NIH post-doctoral fellow in the Biological Laboratories at Harvard University from 1972 to 1974 and then a National Academy of Sciences Exchange Scientist at Moscow State University from 1974 to 1975. From 1975 to 1979 he was an Instructor in Physiology in the Department of Physiology at Harvard Medical School. In 1979 Dr. Sulzman joined the Department of Biological Sciences of the State University of New York at Binghamton as an Assistant Professor and then as an Associate Professor in 1982 and Director of the graduate program in 1983. His research during this time involved basic and applied studies on circadian rhythms, and various aspects of space physiology; this work was supported by NIH, NASA and other agencies. Dr. Sulzman joined NASA Headquarters in 1985 as Manager of the Biomedical Research Program and was appointed to the Senior Executive Service in 1987. He is currently the Lead Scientist and Acting Deputy Director of the Life Sciences Division.

Mr. Alan Thirkettle

Mr. Thirkettle has been project manager of the Columbus Laboratory, the ISS Cupolas, and Nodes 2 and 3 since 1996. He has degrees in Aeronautical Engineering and Aircraft Design from London University and Cranfield Institute of Technology. Mr. Thirkettle joined the European Space Agency in Dec 1973 as the Spacelab Structural Engineering manager at ESTEC, the Netherlands, served as the ESTEC representative for the Spacelab Integration and Test Phase at Bremen, Germany, and led the European Resident Spacelab team at Kennedy Space Center through the first four operational flights. He has worked in the Columbus and Hermes programmes, working on the Columbus laboratory, European Robot Arm, ESA/RSA joint EVA Suit development, and Automated Transfer Vehicle studies.

Dr. Eugene H. Trinh

Eugene H. Trinh is the incoming Director of the Microgravity Research Division at NASA Headquarters. He recently left his position as a Senior Research Scientist at the Jet Propulsion Laboratory, California Institute of Technology in Pasadena, California, where, for twenty years, he has conducted experimental and theoretical research in Fluid Dynamics, Fundamental Materials Science, and protein crystallization using levitation technology. As a JPL scientist he has carried out hands-on experimental investigations in Earth-based laboratories, aboard the NASA KC-135 airplane, and on the Space Shuttle Columbia during a fourteen-day long Spacelab mission. While at JPL, Dr. Trinh was the technical group supervisor for research scientists and engineers, the program scientist and manager for a NASA-sponsored technology development program, the Project Scientist for a Spacelab research facility, and the Principal Investigator for a number of independent original research projects. After graduating from a French Lycee in Paris, he came to the United States where he first received his Bachelor of Science in Mechanical Engineering from Columbia University, and then Master and Doctorate degrees from Yale University.

Dr. Charles Walker

Charles Walker is space systems business development and marketing senior manager for The Boeing Company in Washington D.C. Dr. Walker is an engineer and researcher who has also been an astronaut aboard three Space Shuttle missions. His work included zero-gravity purification of biomedical preparations, and protein crystal growth in weightless space. Over the past ten years Dr. Walker has participated in the design and development of the International Space Station. Dr. Walker serves on the boards, and as an officer, of numerous not-for-profit and educational space-oriented organizations.

Dr. Laurence R. Young

Laurence R. Young is the Apollo Program Professor of Astronautics at the Massachusetts Institute of Technology, and the Director of the National Space Biomedical Research Institute. He joined the MIT faculty in 1962, and co-founded the Man-Vehicle Laboratory, which does research on the visual and vestibular systems, visual-vestibular interaction, flight simulation, space motion sickness and manual control and displays. In 1991 Professor Young was selected as a Payload Specialist for Spacelab Life Sciences 2. He spent two years in training at Johnson Space Center and served as Alternate Payload Specialist during the October 1993 mission. Professor Young has been a Visiting Professor at the ETH (Swiss Federal Institute of Technology) and the Zurich Kantonsspital, a Visiting Professor at the Conservatoire des Arts et Metiers, Paris, a Visiting Scientist at NASA's Ames Research Center, and a Visiting Professor of Electrical Engi-

neering at Stanford University. The Aerospace Human Factors Association awarded him its Paul Hansen award in 1995. He was President of the Biomedical Engineering Society in 1979 and was its Alza Lecturer in 1984. In May 1998 he received the prestigious Koetser Foundation Prize in Zurich, for his contributions to neuroscience.

Dr. Weija Zhou

Dr. Zhou received the B.S.M.E. degree from Shanghai Jiao-Tong University in China, in 1982, a M.S. in Electrical Engineering, M.S. in Mechanical Engineering and Ph.D degrees from the University of Wisconsin-Madison in 1989 and 1992, respectively. Dr. Zhou is a Director with the Wisconsin Center for Space Automation and Robotics (WCSAR), University of Wisconsin-Madison. WCSAR's technical expertise is in the development of controlled environment plant growth facilities for both space-based and terrestrial applications, the enhancement of gene transformation efficiency using the microgravity environment, and the acceleration of commercial crops growth cycle. From 1992 to 1994, he was a chief engineer at WCSAR, where he worked on research and development of the Astroculture flight hardware, a plant growth unit for conducting space-based plant experiments. From 1994 to 1995, he was a project manager at WCSAR, where he worked on the development of a Shared Multi User Remote Robotic Facility (SMURRF), a miniature six degrees-of-freedom manipulator to perform space-based experiments. Since 1995, he has been a payload developer (PD) at WCSAR, where he is in charge of the development of the Astroculture (ASC), Advanced Astroculture (ADVASC), and Commercial Plant Biotechnology Facility (CPBF) payloads. From 1997 to March 1999 he was an Assistant Director. His major responsibility was charge of the center's technology development and commercialization of such technologies.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operation and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503

1. AGENCY USE ONLY *(Leave Blank)*	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	June 2000	Conference Publication

4. TITLE AND SUBTITLE
The Spacelab Accomplishments Forum

5. FUNDING NUMBERS

6. AUTHORS
J. Emond,* Editor; N. Bennett,** Compiler; D. McCauley,*** Compiler; K. Murphy,**** Compiler

7. PERFORMING ORGANIZATION NAMES(S) AND ADDRESS(ES)
George C. Marshall Space Flight Center
Marshall Space Flight Center, AL 35812

8. PERFORMING ORGANIZATION REPORT NUMBER
M–982

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Washington, DC 20546–0001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
NASA/CP—2000–210332

11. SUPPLEMENTARY NOTES
Proceedings of a forum held in Washington, D.C., March 10–11, 1999. Sponsored in part by the National Research Council and the Boeing Company. *NASA Headquarters, Washington, D.C.; **Universities Space Research Association, Huntsville, AL; ***University of Alabama in Huntsville, Huntsville, AL; ****Mevatec Corporation, Huntsville, AL.

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified-Unlimited
Subject Category 99
Standard Distribution

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

This document is a record of the Spacelab Accomplishments Forum held in March 1999. Presentations made at the Forum covered the design, engineering, utilization, and science associated with Spacelab, as well as the international associations and impact of Spacelab and its use in the design and utilization of the *International Space Station*. Topics included Earth observations, space science, life science, commercial uses, microgravity science, and international participation.

14. SUBJECT TERMS
Spacelab, space transportation system history, microgravity research

15. NUMBER OF PAGES
387

16. PRICE CODE
A17

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	Unlimited

National Aeronautics and
Space Administration
AD33
George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama
35812